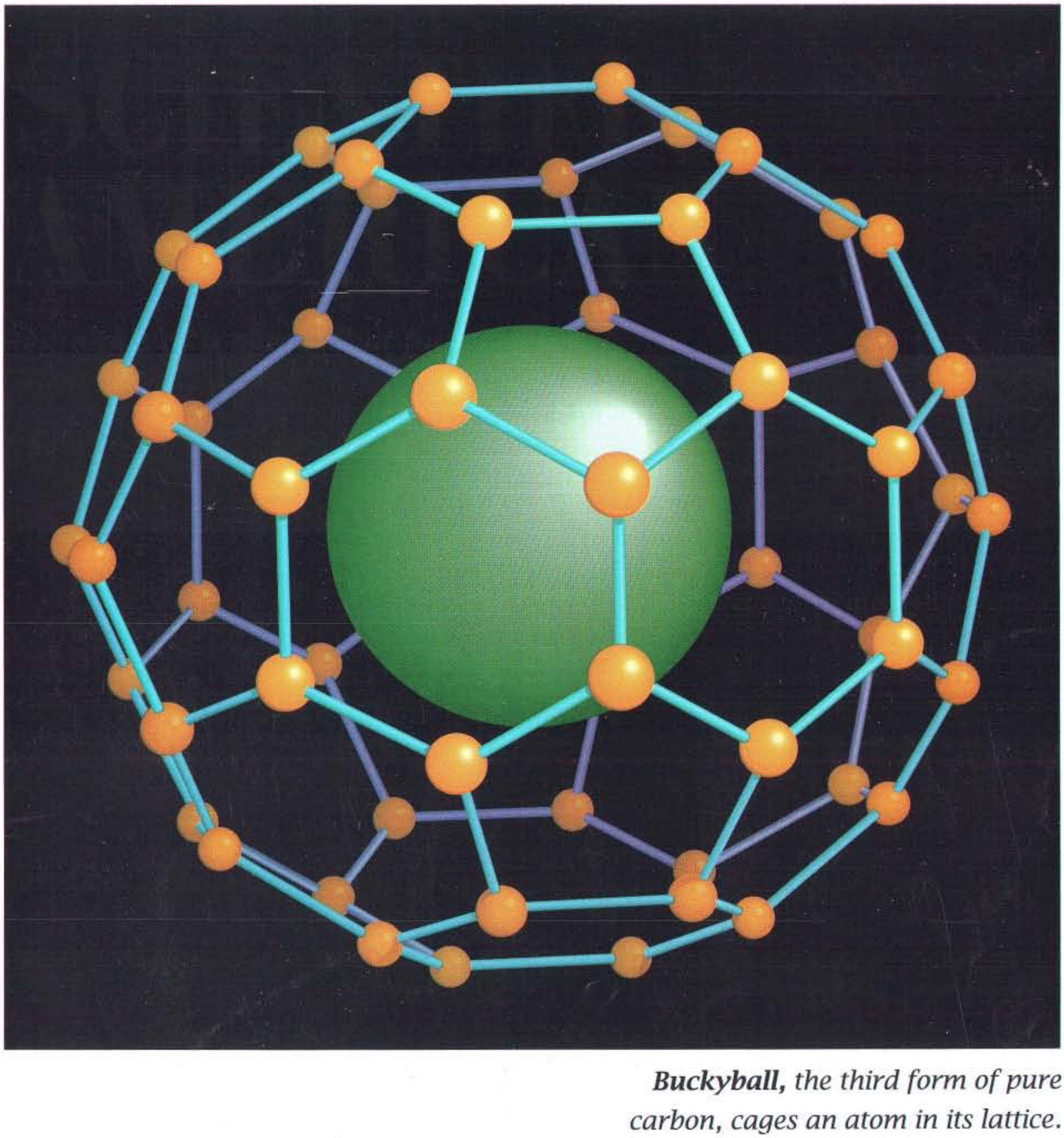
SCIENTIFIC AMERICAN

OCTOBER 1991
$3.95

Remnants of a planet that failed to form.

Still no technological fix for oil spills.

What made higher life-forms possible?



***Buckyball,** the third form of pure carbon, cages an atom in its lattice.*

Where in the world is the true spirit of enterprise to be found?

1990:
John Asmus uses lasers
to restore Qin Dynasty
terracotta army.

1990:
Les Stocker establishes
Europe's first wildlife
teaching hospital.

1981:
Rodney Jackson
uses radio-collars to
track Himalayan snow
leopards.

1978:
Bill Lasley
discovers how to
breed threatened birds
in captivity.

1990:
Wayne Moran
recreates the
sea-voyage of
Marco Polo.

1987:
Nancy Na
uses Buddh
teaching
to promo
conservatio
Thailand

1984:
Donald Perry
invents a device
to aid tropical
rain forest
research.

1984:
Martine
Fettweis-Viénot
records Mayan
wall paintings.

1990:
Suryo
Prawiroatm
creates a
environme
education ce

1990:
Anita Studer starts
reforestation
project in Brazil.

1981:
Milan Mirkovic
cultivates
jojoba plants in
the desert.

1987:
Johan Reinhard
studies Andean
mountain-top
ceremonial sites.

1984:
Kenneth Hankinson surveys
Brabant Island, Antarctica.

1987:
Jacques Autran helps
island-dwellers in
the Indian Ocean.

The 1993 Rolex Awards for Enterprise.

Ever since their inception in 1976, the Rolex Awards for Enterprise have attracted thousands of applications from all around the world.

Now, once again, we are issuing this worldwide call for entries from people who can demonstrate the true spirit of enterprise in their chosen fields of endeavour.

Enterprise recognised.

The five individuals whose projects most impress the Selection Committee will each receive an award of 50,000 Swiss Francs, together with a specially inscribed gold Rolex chronometer. To date, 25 supremely enterprising people have benefited from these premier awards, while dozens of others have received Honourable Mentions.

A choice of categories.

We are now seeking proposals for original projects that fall within any one of the following categories: Applied Sciences and Invention; Exploration and Discovery; The Environment. Within these three broad categories, the Selection Committee will be looking for projects which not only display the true spirit of enterprise and originality but which are also feasible.

When the results are announced in 1993 a hardback book will be published containing details of many of the best entries. The publicity given to projects by previous editions has often led to the entrant receiving additional support from a wide range of sources.

How to apply.

To obtain an official application form together with the rules and conditions for entry, write to: The Secretariat, The Rolex Awards for Enterprise, P.O. Box 178, 1211 Geneva 26, Switzerland. The Awards will be presented in Geneva at the end of April 1993.

ROLEX
of Geneva

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The Rolex Awards for Enterprise
Created by Montres Rolex S.A. to encourage outstanding personal enterprise

SCIENTIFIC AMERICAN October 1991 Volume 265 Number 4

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Iron Deficiency

Nevin S. Scrimshaw

Although it is often overlooked, iron deficiency is the most widespread nutritional problem in the world. It is particularly severe in those developing countries where parasitic diseases compound the effects of inadequate diet. Prevention is the best solution to a condition that can irreversibly damage brain function and impair the immune system—and that may even be fatal.

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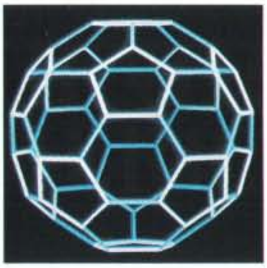

Fullerenes

Robert F. Curl and Richard E. Smalley

The quest for "buckyballs" has been one of the hottest in chemistry. These hollow cages of carbon atoms were characterized in 1985 and dubbed "buckminsterfullerenes" after the inventor of the geodesic dome. Bulk quantities were made in 1990. With other materials, they form crystals having properties that range from superconductivity to ferromagnetism.

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End of the Proterozoic Eon

Andrew H. Knoll

Microscopic, single-celled organisms inhabited the earth for nearly four billion years. Then, just 600 million years ago, the macroscopic ancestors of modern plants and animals suddenly appeared, signaling the end of the Proterozoic eon. What caused the abrupt change? Evidence suggests that a rapid increase in atmospheric oxygen made multicellular life possible.

50

How the Immune System Learns about Self

Harald von Boehmer and Pawel Kisielow

The immune system can identify and destroy hundreds of millions of foreign substances. Yet when it functions properly, it ignores the tissues of the body. How these specialized cells learn to tell "self" from "nonself" has been debated for decades. Now researchers have unraveled one of the processes: the deletion of immature clones of antiself cells by the thymus.

60

Natural Selection and Darwin's Finches

Peter R. Grant

Charles Darwin despaired of ever seeing evolution taking place. The process, he believed, was so slow that only the long-term results could be observed. Fortunately, he was wrong. Numerous studies document natural selection in real time. A classic example is the finches of the Galápagos, populations of which are altered significantly by a single season of drought.

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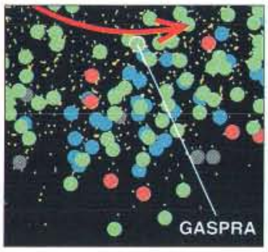
The Origins of the Asteroids

Richard P. Binzel, M. Antonietta Barucci and Marcello Fulchignoni

In the 19th century the search for a "missing" planet ended in the discovery of asteroids. Today astronomers believe they are remnants of a planet that never formed. By studying the asteroids, investigators are revealing important clues to understanding the birth of the solar system.



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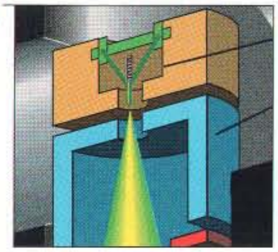
Focused Ion Beams

Jon Orloff

Soldering irons are not much use on wires that are a mere micron in diameter. That is why most defective integrated circuits are simply discarded. But chip makers now have a new tool. Liquid-metal ion sources produce beams of charged ions that can machine and weld as well as implant dopants.



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TRENDS IN ENVIRONMENTAL TECHNOLOGY

Soiled Shores

Marguerite Holloway and John Horgan

After the *Exxon Valdez* oil spill in 1989, the beaches of Prince William Sound were scrubbed, hosed, hoed, fertilized and bulldozed at a cost of $2.5 billion. Some scientists assessing the effects of that effort conclude that no method worked very well; some did more harm than good. The massive spill in the Persian Gulf is likely to teach that sobering lesson once again.

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Hybrid wolves and endangered species.... A younger Eve.... Why do deformed nuclei spin in step?... Greenhouse gas from quiescent volcanoes.... Dyslexic computer chips.... Digital parser.... PROFILE: Biochemist Gertrude Belle Elion.

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Science and Business

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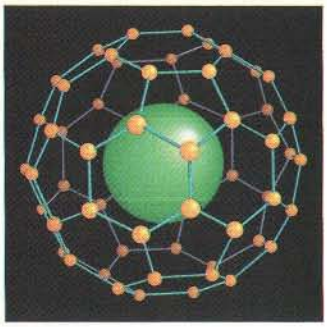

THE COVER portrays a 60-atom carbon cage, known as buckminsterfullerene, encasing an atom of uranium. The cage, the most symmetric molecule possible, was detected in 1985 by the authors of "Fullerenes" (see page 32) and made in bulk quantities only last year. Since then, an avalanche of research has shown the fullerenes to be versatile building blocks. They can be mixed with other materials—placed inside or outside the carbon cage—to make crystals whose properties range from superconductivity to ferromagnetism.

THE ILLUSTRATIONS

Cover illustration by Ian Worpole

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LETTERS TO THE EDITORS

Rambling or Reasoned?

In vain I have read and reread John Kenneth Galbraith's rambling essay, "The Sting of Truth" [SCIENTIFIC AMERICAN, May], searching for some cogent objectivity. If this essay were only the disorganized meanderings of a frustrated moralist lamenting the nasty behavior of the human race, it might be dismissed. But this is the supposed doyen of American theoretical economists addressing us through the supposedly respectable *Scientific American*.

PAUL THERRIO
San Diego, Calif.

Galbraith's rhetoric about the military-industrial complex is strong, but it needs some factual substantiation. The size of the military budget ($300 billion) amounts to $1,200 for every person in this country. Does a family of four really need to spend $4,800 a year to defend itself against a perceived threat from afar?

The magnitude of what could be accomplished with the peace dividend is worth considering. Just 3.3 percent of the military budget could provide one million $10,000 college scholarships. Another 3.3 percent could build 10 subway lines at $1 billion each; in 10 to 20 years all our major cities could have reliable mass-transit facilities. The advantages of a 25 percent cut are obvious.

CONRAD S. REVAK
Pittsburgh, Pa.

Kuwait's Dark Days

In "Up in Flames" ["Science and the Citizen," SCIENTIFIC AMERICAN, May], which concerned research on the potential concentrations of smoke from the oil-well fires in Kuwait, a quote reporting my views was extracted from an article in *Science*. Because of Department of Energy restrictions, I was unable to discuss the results with your writer. Although the quote is accurate, the context is missing, which gives the incorrect impression that the people in Kuwait and in Los Angeles would experience similar exposures to smoke.

Our calculations used a global model to evaluate the climatic effects. We could only estimate the regional- and global-scale smoke concentrations; regional scale is meant to indicate an area on the order of 100,000 square kilometers or more. For an assumed smoke injection of 50,000 metric tons per day (roughly the equivalent of burning between three and five million barrels of oil per day), and assuming a two-kilometer-deep layer, the peak regional smoke densities were about 25 micrograms per cubic meter. The model showed lower concentrations over much of southern Asia and the Pacific Ocean.

For context, Tica Novakov of the Lawrence Berkeley Laboratory reports that peak ground-level concentrations of soot in European air-pollution episodes have exceeded 100 micrograms per cubic meter (during the 1940s and 1950s, the worst day in London exceeded 500 micrograms per cubic meter) and that the monthly average in the Los Angeles area is about seven to 10 micrograms per cubic meter, with levels several times higher during individual hours. The skies would not appear as dark in Los Angeles as in the Persian Gulf region, however, because the depth of the polluted layer would be less.

The contextual omission was thus that the model predictions were regional values. We always recognized that concentrations near the plume would be many times higher, as the people in Kuwait are now experiencing.

MICHAEL C. MACCRACKEN
Atmospheric and Geophysical
Sciences Division
Lawrence Livermore National
Laboratory

Common Horse Sense

It is common knowledge to any exercise physiologist that short sprinting performance is an anaerobic activity. The longer the distance, the more the reliance on aerobic metabolism, in part to prevent the buildup of lactic acid. Patrick Cunningham ["The Genetics of Thoroughbred Horses," SCIENTIFIC AMERICAN, May] has it backward. He states that sprinting in horses is mainly an aerobic activity and that longer races require shifting mainly to an anaerobic energy supply. That is not to deny, however, that the ability to clear lactic acid from the muscles and the blood could be a major limiting factor in long-distance running.

BERND HEINRICH
Department of Zoology
University of Vermont

Cunningham replies:

Professor Heinrich is correct: the labeling of the energy sources for sprints and longer races is reversed in my article. Lactic acid is produced by anaerobic activity only and so accumulates from the start. Yet lactic acid clearance is the first physiological parameter to become critical. Over the same range, oxygen supply increases linearly. The main mechanism for lactic acid clearance is by oxidation in the lungs, so it clearly depends on oxygen uptake. It appears, however, that a linearly increasing oxygen supply does not guarantee a linear rate of lactic acid removal.

UFOs Are Real

Your recent news story concerning mysticism and superstition in the Soviet Union ["Science and the Citizen," SCIENTIFIC AMERICAN, June] mentioned "belief in UFOs" when the writer really meant something like "belief in flying saucers with alien beings aboard." UFOs are unidentified flying objects, a term that has nothing at all to do with belief but rather with an inability to identify an object in the sky. As an astronomer, I spend some of my time dealing with reports from the public (including some very educated people) concerning unusual sky sightings, most of which can be readily explained as astronomical, meteorological, physical or artificial phenomena. Most people are not accustomed to looking at the sky; astronomers and meteorologists are trying to change this. A distinction should be made between those who are curious enough to learn about realistic explanations and those who insist they are seeing spacecraft and beings from other worlds.

DANIEL W. E. GREEN
Smithsonian Astrophysical Observatory

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Japan Airlines

A WORLD OF COMFORT

50 AND 100 YEARS AGO

OCTOBER 1941

"The Cavalry has had a mechanized force since 1931, and the infantry has been experimenting with tanks since the World War, but our scheme for employment of tank units was based largely on British and French concepts, which made such forces subordinate parts of larger, usually infantry, organizations. The latter were not mechanized and could move only about one-tenth as fast. Opposed to this was the German idea of a large, smashing battle force—a complete armored unit of all needed arms—which could penetrate enemy lines and hold the gains thus made, independently of other support. The crushing success of Nazi *schnell truppen* in 1939–40 left no doubt as to which of these two theories was correct, and the United States Army began to reorganize its mechanized units accordingly."

"Whence came oil? If the Earth was born out of the Sun, then it should be elementally similar to its parent—which it is. Also, a spectroscope at The Mount Wilson Observatory recently revealed that substances which are either oil or closely akin to it do exist in the Sun's atmosphere. Then, too, we know that some of the meteorites which fall to earth contain asphalt. Why is it not logical to suppose that oil might have arrived on earth ready-made? The idea is intriguing, but it does not fit the facts that geologists have uncovered. For, if this scheme were true, oil could be found almost anywhere on Earth; whereas it is found in large quantities only in certain kinds of rocks in certain special areas. These are the stratified rocks, formed long eras after the Earth was born. The theory which is currently believed to come close to the truth is that oil probably was formed in the strata deposited on the ancient sea bottoms."

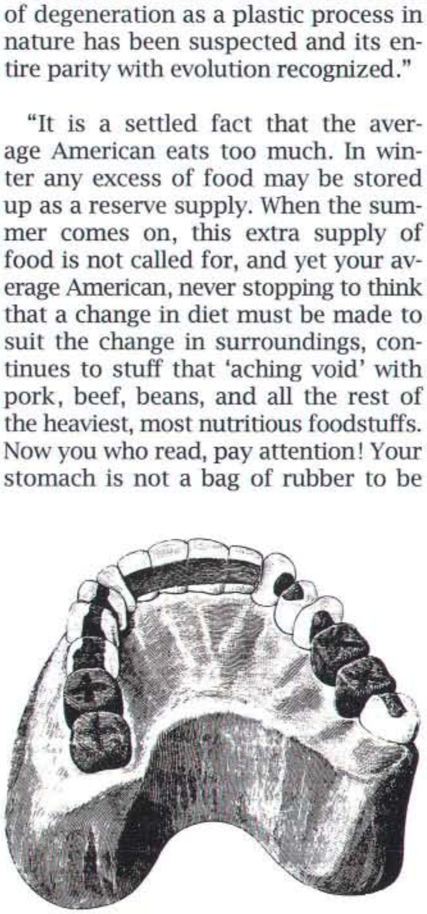
"The strange phenomenon of 'carbohydrate cataract' was discovered by Dr. Helen Swift Mitchell, research professor in nutrition at the Massachusetts State College. Rats, unlike human beings, are not adapted by evolution to the assimilation of the simple sugar galactose. So by simple feeding methods she has been able to bring sugars to a high concentration in the blood of rats, and when this very high level of sugar is maintained through several weeks, all stages of senile cataract of the human type, as well as human diabetic cataract, seem to run a hasty course."

SCIENTIFIC AMERICAN

OCTOBER 1891

"Mr. H. G. Wells, writing for the *Gentleman's Magazine* (London), says: In the popular conception, life began with the amoeba, then came jelly fish, shell fish, and a miscellaneous mass of invertebrates; then real fishes and amphibia, reptiles, birds, mammals, and man, the last and first of creation. This is not the teaching of science. On the contrary, biology, along with advance, teaches retrogression as its essential component. Isolated cases of degeneration have long been known. It is only recently that the enormous importance of degeneration as a plastic process in nature has been suspected and its entire parity with evolution recognized."

"It is a settled fact that the average American eats too much. In winter any excess of food may be stored up as a reserve supply. When the summer comes on, this extra supply of food is not called for, and yet your average American, never stopping to think that a change in diet must be made to suit the change in surroundings, continues to stuff that 'aching void' with pork, beef, beans, and all the rest of the heaviest, most nutritious foodstuffs. Now you who read, pay attention! Your stomach is not a bag of rubber to be stretched to its greatest powers of endurance, nor should the sensation of complete satiety be taken as the index of the quitting point.—*S.A.G., Texas Health Journal*."



An improvement in dentistry

"A.J.B. asks: What constitutes a perpetual motion? I have a water motor that when set in motion drives the water wheel, and the same water is conveyed back to the original starting point. If I have made a new discovery, please inform me in your next issue. *A. The apparatus you describe, if operative, would be classed as a perpetual motion. But to us it looks like a no go.*"

"The widespread sails of a ship, when rendered concave by a gentle breeze, are most excellent conductors of sound. A ship was once sailing along the coast of Brazil, far out of sight of land. Suddenly several of the crew noticed that when passing and repassing a particular spot they always heard with great distinctness the sound of bells chiming sweet music, as though being rung but a short distance away. Several months afterward, upon returning to Brazil, the sailors were informed that at the time when the sounds were heard, the bells in the cathedral of San Salvador, on the coast, had been ringing to celebrate a feast held in honor of one of the saints. Their sound, favored by a gentle, steady breeze, had traveled a distance upward of 100 miles over the smooth water, and had been brought to a focus by the sails."

"If it is true, as cabled, that 300 h.p. gathered from the river Neckar is being delivered at the Frankfort exposition, 108 miles distant, in the form of electrical energy and with a loss of only 25 per cent, it is an event of uncommon importance likely to awaken as much interest in other parts of the world as at the chief city on the Main."

"Our present engraving illustrates a notable improvement in the art of dentistry, of which Dr. J. W. Clowes, of New York City, is the author. The invention consists in fillings inserted in cavities in approximate faces of contiguous teeth, said fillings resting directly upon the gums, and being formed of a single body of material connecting the teeth so that they mutually support each other."

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These state-of-the-art solutions are a striking testimony of Philips dedication to the mobile telecommunications market.

Philips. In perfect shape today, to further shape the future of telecommunications tomorrow.

Excellent reasons to go to Geneva in October to see Philips at Telecom '91.

Telecommunications, talk with Philips!

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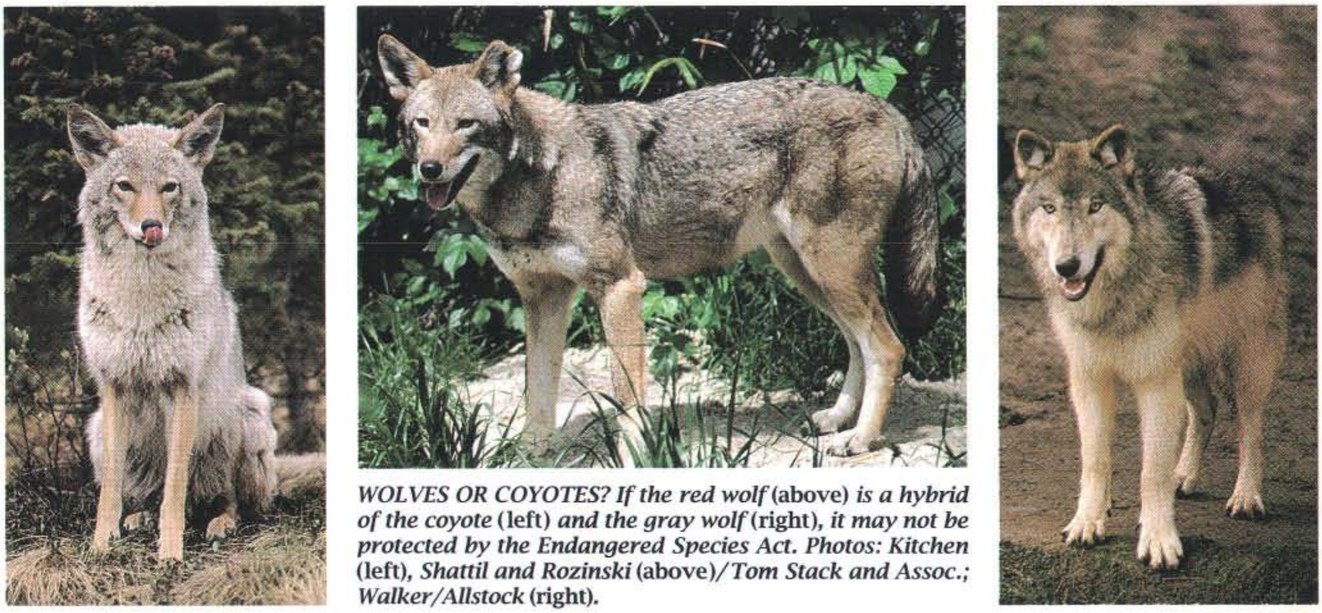
SCIENCE AND THE CITIZEN



WOLVES OR COYOTES? If the red wolf **(above)** *is a hybrid of the coyote* **(left)** *and the gray wolf* **(right)**, *it may not be protected by the Endangered Species Act. Photos: Kitchen* **(left)**, *Shattil and Rozinski* **(above)/***Tom Stack and Assoc.; Walker/Allstock* **(right).**

Howls of Dismay

If red wolves are coyotes, they could lose protection

The howls of red wolves that echo over the Alligator River National Wildlife Refuge in North Carolina have new reason for sounding mournful. Once abundant in the southeastern U.S., the wolves became officially extinct in the wild in 1975; only by placing all the animals in captivity were conservationists able to save them. Those few now living in Alligator River were released there by the U.S. Fish and Wildlife Service in 1987. If all goes well, red wolves will be reintroduced into the Great Smoky Mountains National Park in North Carolina this autumn.

Yet the animals might also now be on the verge of losing their protection under the Endangered Species Act. The reason: new genetic evidence suggests that red wolves are hybrids and not a true species at all.

Questions have hung over the species designation for red wolves ever since it was first applied in 1851. Red wolves are smaller than gray wolves but larger than coyotes, which prompted speculation that they might actually be hybrids of the two. Wolves usually kill coyotes that enter their territory, notes Robert K. Wayne, the head of conservation genetics of the Zoological Society of London; nevertheless, they will occasionally mate if no other wolves are available.

Wayne and Susan M. Jenks of the University of California at Berkeley became involved with red wolves of the southeast after studying hybridization between gray wolves and coyotes in Minnesota and Canada. The researchers analyzed sequences of red wolf DNA extracted from the energy-producing organelles called mitochondria; they then compared the sequences with those of coyotes and of gray wolves. They also checked the mitochondrial DNA in blood samples taken from red wolves in the 1970s and in the pelts of old museum specimens. As Wayne explains, "We went in thinking that we would find some unique genetic markers."

They were wrong: in every case, the red wolves appeared to be genetically identical to either coyotes or other species of wolf. One inescapable possibility is that red wolves are nothing more than hybrids. Another explanation is that red wolves crossbred with other species so long ago and so extensively that their genetic distinctiveness has essentially disappeared.

"Of course, we sort of knew that already," observes Gary Henry, the red wolf project coordinator for the Fish and Wildlife Service. Of the 40 red wolves collected during the mid-1970s, he reports, only 17 were finally deemed genetically pure enough to participate in the breeding program. Henry regards the Wayne and Jenks study as just one dissenting piece of evidence in an assortment that generally favors a species designation for red wolves.

Ronald Nowak of the Fish and Wildlife Service, who has studied the history of canines in North America, goes one step further. He believes red wolves are in fact the progenitors of all other wolves. "I see animals in the fossil record that have all the characteristics of the red wolf going back hundreds of thousands of years," Nowak says.

Henry notes that a much stronger case for or against the species status of red wolves will be made after DNA from the cell nuclei is analyzed as the mitochondrial DNA was. Nuclear DNA contains the genes that are primarily responsible for an organism's characteristics. Wayne says his laboratory is currently working on comparisons of the nuclear DNA.

The result of that study could strongly affect the red wolf's future. According to Michael J. Bean, a senior attorney for the Environmental Defense Fund, "the question of whether the Endangered Species Act protects hybrids has been answered three different ways at three different times by the lawyers for the Department of the Interior." A spokesperson for the Department of the Interior reports that it does not currently have a position on the matter but that a statement may

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The Fish and Wildlife Service has no plans to discontinue the red wolf project even if the animals are not covered by the Endangered Species Act. Nevertheless, the loss of that protection could put the mandate for the project—budgeted at $600,000 for this year, according to Henry—up in the air.

John L. Gittleman and Stuart L. Pimm, conservation biologists at the University of Tennessee, believe that if red wolves prove to be hybrids, the efforts to save them should be redirected. "Saving species is a very expensive business, and we obviously can't save everything," Pimm remarks.

In an article that accompanied the Wayne and Jenks paper in *Nature*, Gittleman and Pimm argue for an emphasis on saving "keystone species": organisms that are critically important for preserving entire habitats. The top predators in an ecosystem usually meet that criterion, so saving "charismatic megavertebrates" like gray wolves would make good sense, Pimm says.

Saving red wolf hybrids might not. Coyotes have already filled much of the wolves' former ecological niche, Gittleman and Pimm maintain. If red wolves were to vanish, they say, their genes would still survive in gray wolves and coyotes. Even Henry admits that if frequent crossbreeding between the reintroduced red wolves and coyotes seemed to be an unavoidable problem, the Fish and Wildlife Service might someday have to reexamine the value of trying to preserve the wolves.

Wayne believes protection for the red wolf should continue. Even if the animal is a hybrid, he points out, resurrecting it from gray wolves and coyotes may be impossible. No red wolves appear in Minnesota or Canada, despite the extensive crossbreeding that occurs there. "The environmental and genetic conditions that gave rise to the red wolf may have been unique," Wayne says.

One general problem highlighted by the red wolf situation is the difficulty of designing and executing legislation to promote sensible conservation measures. "The problem with the Endangered Species Act is that there's not much flexibility built into it," Wayne suggests. Although protection for red wolves as hybrids would be beneficial, he believes hybridization between gray wolves and coyotes should be prevented because it dilutes the purity of the gray wolf stock.

"It would be nice if one could have additional protection for special ecosystems" instead of just targeting endangered species, Pimm observes. Nevertheless, he adds that anything resembling an Endangered Ecosystem Act would be difficult to devise without weakening the Endangered Species Act.

Bean takes a harder line: "A lot of the sentiment one sometimes hears that we need an Endangered Ecosystem Act is born out of frustration over the failure of the Endangered Species Act to deliver all that it promised," he says. "That failure is the result of having too few dollars and too little spine in the backs of the administrators." —*John Rennie*

Greenhouse Gusher

Not all volcanoes are ill mannered. Some evidently spew forth tremendous quantities of invisible carbon dioxide in a surprisingly surreptitious manner. Mount Etna, an active but, at present, relatively subdued volcano in Sicily, is a case in point.

A team of French researchers recently discovered that Mount Etna is one of the earth's most potent natural sources of carbon dioxide. They found that it quietly pumps some 25 million tons of carbon dioxide into the atmosphere each year, roughly 20 times the amount unleashed by far more spectacular volcanoes, such as Kilauea in Hawaii.

Mount Etna's extraordinary exhalations were measured by a team of researchers led by Patrick Allard of CNRS in Gif-sur-Yvette, France. Because concentrations of carbon dioxide in the volcano's plume are difficult to measure directly, Allard and his colleagues looked instead at sulfur dioxide emissions in the plume and then combined these with estimates of the relative abundance of the two gases.

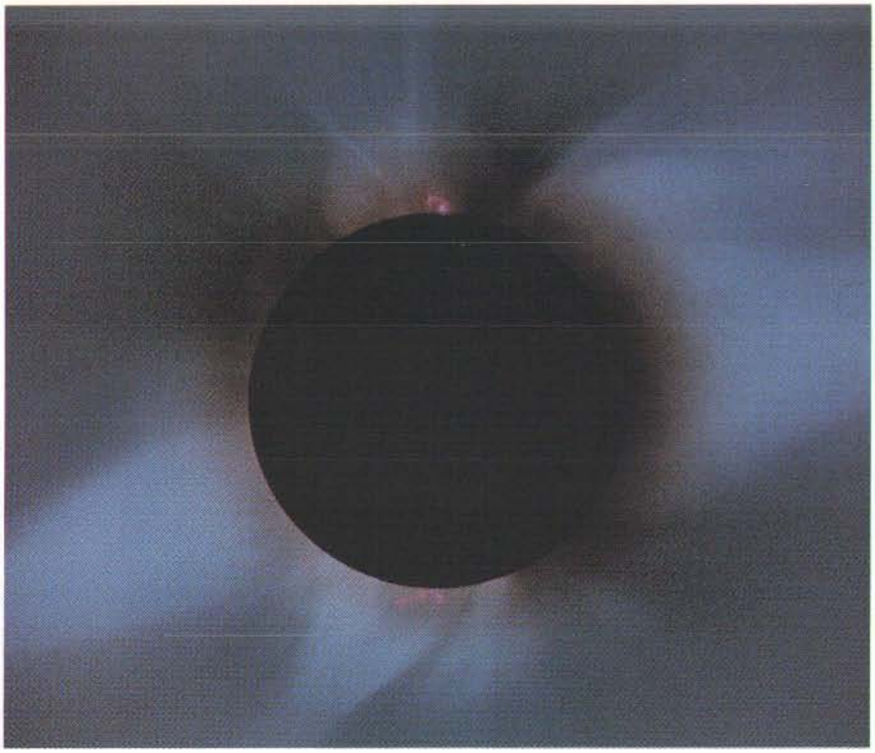
That calculation alone gave a very high value for carbon dioxide emissions from Mount Etna, but the French scientists knew from previous studies that the entire region around the volcano is enriched in carbon dioxide. A careful study of the nearby air and soil revealed that the amount of gas that diffuses invisibly through the volcano's peaceful outer flanks is at least comparable to the amount released from the volcano's crater.

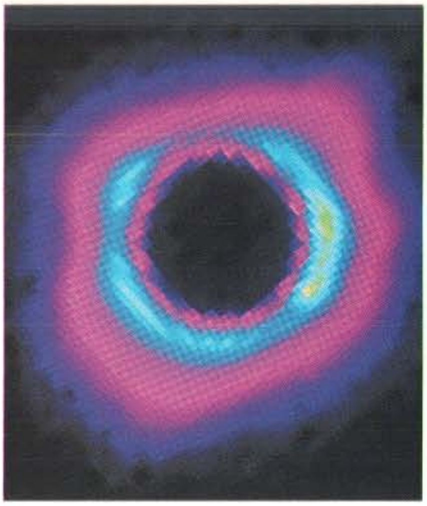
Allard suggests that Mount Etna's copious emissions might derive from carbon dioxide being cooked out of carbon-rich rocks under the volcano. But Terrence M. Gerlach of the U.S. Geological Survey, who has studied many of Mount Etna's eruptive peers, thinks the volcano's behavior is probably just an extreme example of a class of volcanoes whose lavas are relatively alkaline.

MOUNT ETNA emits CO_2. Photo: Giansanti/Sygma.

Human activities now release carbon dioxide at approximately 900 times the rate that Mount Etna does, Gerlach observes. In the past, however, the long-term flow of carbon dioxide from volcanoes was crucial to sustaining the natural greenhouse effect. Slow but steady weathering processes tend to remove carbon dioxide from the air. The prodigious output of Mount Etna helps pinpoint where the carbon dioxide came from that made up for this deficit.

Not all the lessons of Mount Etna are quite so theoretical. In 1986 the water in a volcanic lake in Cameroon overturned, suddenly liberating large amounts of dissolved carbon dioxide. The gas flowed over local villages, smothering 2,000 people. Most likely, the carbon dioxide seeped into the lake Etna-style, directly through the seemingly quiescent volcano. Even when they are being subtle, volcanoes can be deadly. —*Corey S. Powell*





Sol's Plumage

The eclipse provided a close look at the corona

Few travelers to Hawaii anticipate doing much work. But the astronomers who headed for the observatories on Mauna Kea to record the total solar eclipse of July 11 were exceptions. Despite threatening weather, sputterings from a nearby volcano and high-altitude dust from the eruption of Mount Pinatubo, they recorded the event from visible-light to millimeter radio wavelengths.

A primary target for many observers was the solar corona. Serge Koutchmy of the Institute of Astrophysics in Paris, with a dozen collaborators, used filters to photograph the inner structure of the corona [*see photo, top left*]. Such details are normally obscured by the brighter, outer part of the corona. Most obvious are the coronal streamers, consisting of plasma, or ionized gas, that generally follow the sun's magnetic field.

Solar prominences, or gaseous projections that rise up from the sun's surface, are shown in red; a particularly intense prominence near the 12 o'clock position can easily be seen in the closeup [*see photo, below*]. Also apparent is the effect of the Mount Pinatubo eruption. The dust and ash spewed into the upper atmosphere have noticeably brightened what would normally be a deep-blue background.

More exotic images were made by Giovanni Fazio, Eric Tollestrup and their colleagues from the Harvard-Smithsonian Center for Astrophysics, who produced the first infrared images of a solar eclipse. In the false-color image [*see photo, top right*], which was processed by Amber Engineering in Goleta, Calif., the solar prominences visible in Koutchmy's photographs show up as large white patches, and the corona is colored deep purple and blue. (The purple ring around the moon is a measurement artifact.)

Investigators were hoping to find evidence of dust rings around the sun. Such rings "are analogous to the rings around Saturn," Tollestrup explains. The dust is thought to have originated either from a body near the sun that broke up during the formation of the solar system or from material shed by comets and asteroids.

No signs of the putative rings are on the image. Still, "that's not to say we won't find something," Tollestrup says. The rings might be obscured by the bright corona, which is near its maximum. Tollestrup is hoping to use visible-light data to subtract the corona from the infrared image. *—Philip Yam*

Spin Cycle

Rotating nuclei share a few moments of inertia

Imagine an ice skater twirling about the tip of one of his blades. If he subsequently grabs weights in each outstretched hand, he will change his mass and, hence, his moment of inertia. Intuitively, one would guess that his rotation would be different each time he changes mass. But in the subatomic world, intuitive thinking often proves inadequate. Researchers at the Lawrence Berkeley Laboratory have been finding that rapidly spinning nuclei with different masses have similar—if not exactly the same—moments of inertia. "Something's going on," says Frank S. Stephens, a physicist at the Lawrence Berkeley lab, "and for reasons we don't understand yet."

A spinning nucleus results from an off-center collision between two nuclei that fuse to form a rapidly spinning, elongated body. The deformed nucleus can take the shape of an American football, a doorknob or possibly even a banana, depending on the collision energy and the nuclei. In a typically deformed nucleus, the long axis exceeds the two short axes by about a factor of 1.3. Nuclei whose long axis is about twice that of its short ones are called superdeformed.

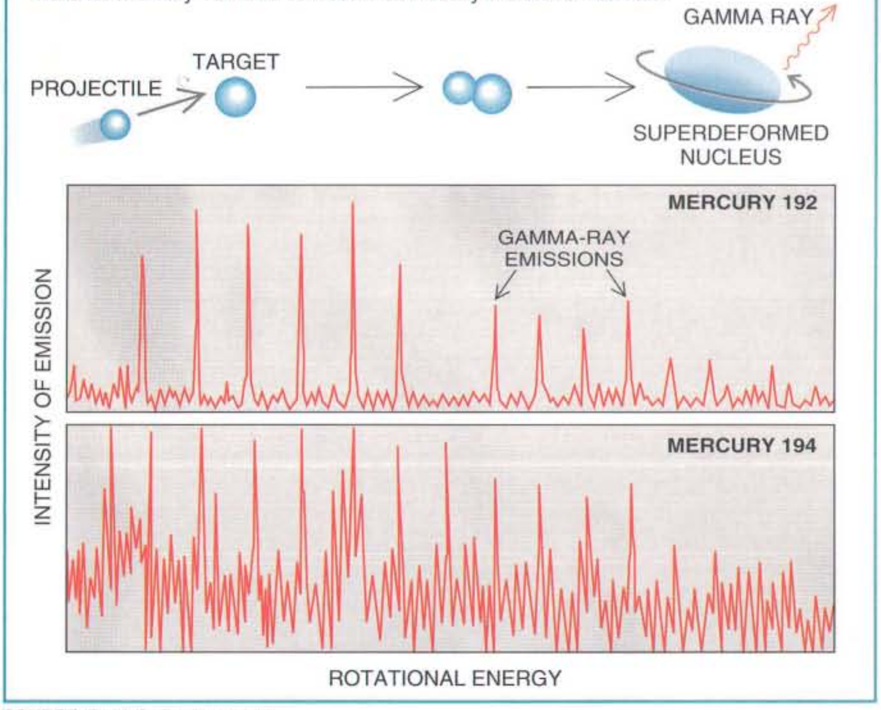
It is in these superdeformed nuclei that curious goings-on have taken place. A spinning, superdeformed nucleus slows down in discrete steps, each time emitting gamma rays, or highly energetic photons. The emissions produce a characteristic band of energy spikes, all spaced equally apart. The surprise: the spectra of some different superdeformed nuclei were almost identical.

In other words, it doesn't matter how many weights the figure skater holds. The nuclei had similar moments of inertia and were losing angular momentum in the same steps. Adding a couple of neutrons to an element might not do anything to the moment of inertia.

The phenomenon was first noticed in 1989, when Peter J. Twin, now at the University of Liverpool, reported identical bands in dysprosium and terbium isotopes. These nuclei consist of about 150 nucleons (protons and neutrons). Since then, researchers from Lawrence Berkeley and the Lawrence Livermore National Laboratory have discovered many other similar bands, especially in nuclei in the mass 190 region, such as mercury, thallium and their isotopes. "These bands introduce features that are new to the study of nuclei," says Richard M. Diamond, one of Stephens's collaborators.

The Spectra of Superdeformed Nuclei

When two nuclei collide, they sometimes fuse to form a rapidly spinning, superdeformed nucleus. The elongated body slows down in steps, emitting a gamma ray each time. Despite having different masses, some superdeformed nuclei have similar moments of inertia, as indicated by their gamma-ray spectra. The emissions shown here for mercury 192 and 194 occur at virtually the same intervals.



SOURCE: Frank S. Stephens et al.

Why the nuclei have similar, if not identical, rotational inertias is not well understood. "In general, one expects variation of the moment of inertia with mass," says Richard R. Chasman, a physicist at the Argonne National Laboratory. Other factors, such as the shape of the nucleus, should "make changes that are bigger than what we are observing," Stephens says. Conceivably, the superdeformed nucleus could be so stable that the angular momentum of the additional nucleons does not affect the gamma-ray spectra. Still, a full explanation "is pretty obscure at this point," Chasman notes.

Although the similar moments of inertia are astonishing in themselves, the spectra surprised the investigators in another way. The position of the peaks in the different bands coincided. The alignment implies that an additional nucleon adds angular momentum in integer or half-integer, or quantized, units. "The particle could have added any amount of angular momentum," Stephens says, adding that in fact "there's no reason it should be quantized."

A partial explanation for the quantized spin alignment may involve a concept called pseudospin. Nuclei can be considered to have shells, or bunchings of energy levels, that protons and neutrons fill up, much the way electrons fill up orbitals of atoms. In the spinning nucleus, the shells spread out, resulting in a reorganization of some nucleons into partial, or pseudo, shells. The intrinsic spins of the nucleons end up pointing along the rotation axis of the superdeformed nucleus. "It doesn't explain everything," Stephens remarks, "but most researchers think that pseudospin has to be involved in some way." Other investigators have proposed that the extra nucleons add no angular momentum whatsoever. Zero, after all, is an integer. But why additional particles would not add any spin is also hard to explain.

Answers to these puzzling phenomena may depend on more sensitive instruments, ones able to tease more information out of the superdeformed nuclei. Such a detector, called Gammasphere, is scheduled to start operating at Lawrence Berkeley early in 1993. The formidably named device will be able to detect gamma rays 100 times weaker than current instruments.

In the meantime, physicists are trying to come up with a single theory to account for all the observed mysteries. "We're at a nice stage right now," Stephens says. "There are a lot of ideas on the market." —*Philip Yam*

Crossed Lines

Eve's family tree may have a few branches from Adam

In 1987 a group led by the late Allan C. Wilson of the University of California at Berkeley traced all human genes of a certain class to a woman who lived in Africa between 150,000 and 200,000 years ago. Some scholars questioned the family tree by which the group placed "Eve" in Africa and the "molecular clock" by which they dated her to so recent a time. But no one quibbled with her sex. The Berkeley team must have traced a pure line of women, all agreed, because they traced genes inherited from the mother alone.

But a recent study of mouse genetics published in *Nature*—among the last papers to which Wilson contributed—has shown that paternal genes can sneak into the mix. The lead author, Ulf Gyllensten of the University of Uppsala, says the effect will probably be observed in humans, too. If he is right, the addition of paternal DNA would throw off the calculation of Eve's age, making modern *Homo sapiens* an even more recent upstart. "If leakage exists in humans," Gyllensten says, "it would put the Eve dates at even later times."

The genes the Berkeley group studied were thought to be a purely maternal bequest because they are encoded not in the DNA of the nucleus, as are most genes, but in organelles called mitochondria that take no part in the mixing of paternal and maternal genes that occurs during fertilization. They are cloned—copied without changes, other than the odd mutation—from a maternal template.

Attempts to find traces of paternal mitochondrial DNA (mtDNA) had failed until now because the available tests

The Danger from Kuwait's Air Pollution

Your eyes itch, your throat rasps, your lungs and head ache. If you dare to exert yourself, you are likely to cough up black phlegm. These are the immediate effects of being downwind of hundreds of oil-well fires ignited by Iraqi soldiers in Kuwait this past February. Little wonder, then, that some U.S. veterans of Desert Storm called it the Black Lung Tour.

Does smoke from the fires—which are expected to burn at least until next spring and possibly much longer—pose a serious threat to the health of people in the region? This past April the U.S. Environmental Protection Agency announced that toxic emissions in Kuwait "were not at levels of concern." But in August, speakers at a conference organized by the Harvard University School of Public Health and Center for Middle Eastern Studies presented a less optimistic view. "Air pollution kills," stated George D. Thurston of the Institute of Environmental Medicine at New York University.

Thurston contended that pollution levels in Kuwait could cause 1,000 excess deaths among the million or so occupants of Kuwait over the course of a year, an increase in the prewar mortality rate of as much as 20 percent. Thurston based his estimate on an analysis of a pollution episode in London in 1952 that resulted in some 4,000 excess deaths in two weeks.

Haluk Ozkaynak of the Harvard School of Public Health arrived at a similar conclusion based on a study of elevated-pollution episodes in New York City and Los Angeles. Those most at risk, Ozkaynak said, include the elderly, children and persons who are already suffering from respiratory and cardiovascular ailments. The mean age of Kuwait's populace is reportedly only 12 years, and more than 10 percent of the population is asthmatic.

Researchers pointed out that many deaths could be averted with an early-warning system that would tell people when to stay indoors, wear masks or take other appropriate steps. Work has begun on such a system, but technical and political problems have delayed its completion. According to U.S. officials, some Kuwaiti authorities are concerned that the implementation of such a system might spur those in the country to leave and discourage those still outside the country from returning.

Virtually all the speakers at the Harvard conference deplored the scarcity of information, including data showing how the smoke affects the internal organs. Although Kuwaiti scientists reported damage in the lungs and hearts of slaughtered sheep, no one had data on the effects on humans.

Such information may be forthcoming, however, from a study by the U.S. Armed Forces Institute of Pathology in Washington, D.C. Colonel John S. Jewell, the institute's executive officer, told SCIENTIFIC AMERICAN that workers have been gathering tissue samples from soldiers who died in Kuwait and Saudi Arabia from both combat-related injuries and other causes. The military investigators intend to search for smoke-induced changes—including cellular or genetic damage and elevated levels of toxins—by comparing the tissues of soldiers killed before the fires were ignited with tissues of those killed afterward.

Jewell acknowledged that the Department of Defense has an ulterior motive for the study: to protect itself from "Agent Orange–type" lawsuits by American veterans who acquire cancer, heart disease, emphysema or other disorders in the years to come and attempt to blame the Black Lung Tour. —*John Horgan*

SMOKE obscures the view in Kuwait City.

were not sensitive enough. The development of the polymerase chain reaction (PCR), however, has enabled workers to amplify faint traces of DNA into robust samples. The sticking point lay in getting sufficiently different mtDNA segments. The human species, for example, shows less than 2 percent variability over all 16,000 base pairs of the mtDNA molecule. It is hard to find any 20-base segments that differ at more than a single base pair. To get paternal genes to stand out, therefore, the father and mother should come from completely different species.

It turns out that the ideal subjects—a hybrid strain of mice—had been bred for other purposes by Dan Wharton, a curator at the New York Zoological Society's Bronx Zoo. He wanted to develop ways of restoring species in which members of one sex, usually the females, have disappeared. Wharton thought he might do so by crossing a surviving male with a female from another species, backcrossing the hybrid offspring with another surviving male from the threatened species and repeating the process. "The first generation derives 50 percent of its genes from the father's species, the second has 75 percent, the third, 87.5 percent; after eight, it's up to 99.6 percent," says Wharton, who has backcrossed the mice through 26 generations in the course of nine years.

When Wilson heard of Wharton's mice, he suggested to Gyllensten, then a postdoctoral fellow in his laboratory, that they would be the ideal testing ground for paternal mtDNA. Wilson reasoned that the backcrossing that had concentrated genes from the father's species must also have concentrated any mtDNA that slipped through. Gyllensten and a colleague at Uppsala took up the challenge.

The Swedish researchers found that one mitochondrion in every thousand derived from the father's species. The authors caution that some mechanism might prevent paternal leakage in crosses within a species. Gyllensten, however, says this seems unlikely.

A mere trickle of Adam's genes could alter the matrilineal picture of human descent in at least two ways. First, a bit of paternal mtDNA might occasionally take over a maternal line, falsely appearing to link it to other lines. Second, it would cause the tree to cover not only females but some males too. By expanding the effective population, leakage distorts the DNA clock.

That clock was derived from a family tree whose branches express genetic distances among many human mtDNA lineages. Such distances result from random mutations, which are presumed to accumulate at a constant rate. Workers calibrated the clock by comparing the genes of humans and chimpanzees, which are believed to have diverged from a common ancestor about six million years ago.

But if the population is larger than had been assumed, some of the genetic diversity must be discounted as the effect not of time but of population size. Gyllensten says his findings suggest that Eve lived "significantly" later than had been supposed. Before he died this past summer, Wilson, evidently relying on Gyllensten's findings, was talking of a date only 75,000 years ago.

Some geneticists cast doubt on all such dates because they depend on the family tree built from a single molecule. Kenneth K. Kidd of Yale University says he hopes to get a more reliable picture of evolutionary history—if not a real clock—by finding tiny sequences in the nuclear genes whose inheritance is very stable over the generations. "One could then get many estimates of time, possibly each one crude," he notes. "But if they converge, you may be able to make meaningful estimates."

Even "Adam" may be traceable through study of parts of the Y chromosome that are inherited from the father alone. Kidd and other workers have found that the "maleness genes" vary more within Africa than outside it. The greater variation in Africa, as seen in both the mitochondria and the maleness genes, indicates that people there had more time to accumulate mutations. Africans would thus have preceded other peoples. Kidd says the work on Adam therefore supports the idea of an African origin for modern humans. But, he adds, no one has yet tried to put a date on the great event.—*Philip E. Ross*

Sharper Image

Picosecond photography may reveal tumors

Early detection is the key to successful treatment of malignant tumors. Transillumination, a technique sometimes used in breast examinations, involves simply shining a light through the soft tissue and looking for a shadow. But it is impossible to see tumors smaller than about a centimeter across because light scatters within the breast. Now researchers at the City University of New York have found a way to improve resolution that may help spot small tumors early in their development.

Scattering happens when many photons "bounce" off molecules as they pass through tissue. But not all photons are scattered. Some pass through in a more or less straight line. The New York researchers, Ping P. Ho, Robert R. Alfano and their colleagues, realized that these "direct path" photons should carry a clear image of any objects—such as tumors—in their path.

The challenge was to separate the useful direct-path photons from scattered photons. Fortunately, there is a way to distinguish the two. Direct-path photons, like express trains, get to where they are going faster than those that make many stops on the way. Ho and co-workers therefore used an ultrafast shutter to photograph just the first wave of photons arriving through a tissue sample that had been illuminated by a sudden flash.

The shutter had to be extremely fast, closing within a few picoseconds (a picosecond is one trillionth of a second). But a device called an optical Kerr gate, which consists of a liquid whose optical properties are altered by light, was up to the task. Precise synchronization was achieved by taking some light from the laser used to illuminate the sample and delaying it by routing it over a longer path with mirrors and prisms. The flash of delayed light was then used to trigger the Kerr gate.

Ho and his colleagues found they could photograph patterns of fine stripes and points of light at submillimeter resolution through 3.5 millimeters of human breast tissue. They could also "see" through three millimeters of chicken breast muscle, which is very fibrous, and through five centimeters of water filled with polystyrene beads. The shorter the time the Kerr gate was left open, the better the resolution. Scattered photons broke up the images when the gate was left open for more than about 20 picoseconds.

The team's goal now is to increase the depth of tissue that the technique can see through. Ho believes two centimeters would be sufficient to start to be clinically useful. To do that, he plans to try a more sensitive, cooled charged-coupled device camera, faster Kerr gates and a more powerful illuminating laser. If his expectations are realized, transillumination might yet become a widely used cancer-screening technique. —*Tim Beardsley*

Word Games

Another attempt to create a universal parsing machine

Building on a linguistic theory of Noam A. Chomsky, researchers at the Massachusetts Institute of Technology are trying to develop a computer program that can decode the grammatical structure of a wide variety of sentences. The workers say that the project, though in a preliminary stage, may be a first step toward one of the most avidly sought and elusive goals of the artificial-intelligence community: a computer program that can translate any human language into any other human language.

The research may also confirm an assertion first made by Chomsky that all languages—from Warlpiri, an Australian aboriginal dialect, to English—spring from a universal "deep grammar" that is hard-wired into the human brain. "That's really what the project is about," explains Robert C. Berwick, an M.I.T. computer scientist who is the project's leader.

Scientists have long attempted to elucidate a formal, logical structure underlying all languages. In the 1950s Chomsky and other linguists thought they could accomplish this task by developing so-called generative grammars, sets of rules that indicated how to construct a grammatical sentence in a given language. But as they examined languages in depth, the rules began to proliferate and to become dizzyingly complex.

About a decade ago Chomsky, who is a professor of linguistics at M.I.T., conjectured that underneath the "epiphenomena" of rules lies a much smaller set of more fundamental linguistic phenomena. Chomsky compared these principles with switches having two or three possible settings. The setting of the switches determines the structure of a particular language, whether Farsi or French. Children can learn language with ease, therefore, because the process involves nothing more than the flipping of the various innate switches into particular settings.

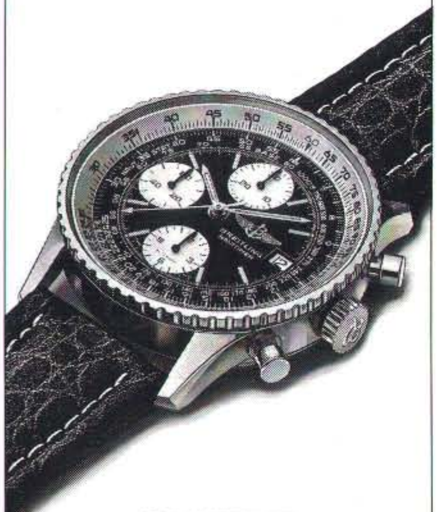
Several years ago Berwick and a group of graduate students, including Sandiway Fong and Bonnie J. Dorr, began trying to create a computer program that could replicate, in a sense, this human capacity. The current computer program consists of 24 principles, each of which has two or three different settings. One principle, for example, seeks to assign each pronoun to its proper antecedent. Another concerns the order of words in such basic linguistic units as predicates (the verb-object part of the sentence) and prepositional phrases; the principle states that the verb appears either at the beginning of the predicate, as in English, or at the end, as in Japanese. Yet another principle seeks to distinguish between words that, though in the same general category, have subtly different "thematic roles," as Berwick puts it. For example, the program would know that "persuade" and "hit," though both transitive verbs, can be followed by different kinds of objects.

Berwick says that this relatively simple design can generate as many as 2^{25} possible sentence structures, just as a few elementary particles can combine to form matter of infinite complexity. When the researchers feed sentences into the computer, it identifies the subject, verb and object, explaining "who did what to whom." One of the program's strengths is that it can parse sentences containing tiny errors of grammar. Although common in human speech, such errors can baffle rule-based programs.

The current program can handle only a few languages, including English, German, Japanese and Warlpiri. The Australian language has long been an object of fascination to linguists, Berwick observes, because subjects, verbs and objects can appear in virtually any order. The program cannot yet translate one language into another. That step would require making it more sensitive than it is to the meaning of words. Berwick notes that given the sentence "John ate the Rocky Mountains," the program would simply acknowledge that the structure is grammatical and parse it rather than pointing out that the sentence is meaningless.

Nor is it yet clear whether the principles and settings identified so far represent a truly comprehensive grammar. It is possible, Berwick acknowledges, that the basic inventory of principles may have to be enlarged or that each principle may require more settings. If that turns out to be the case, the program could become so complicated that its purpose is defeated. "You don't want to end up with as many principles and settings as you had rules," he says.

Nevertheless, Berwick argues that the research has already demonstrated far more than many skeptics had thought possible. "There were certain people who had claimed you couldn't [parse a sentence] with a program based on Chomsky's theory," Berwick remarks. "We've already gone beyond that." —*John Horgan*



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Digital Dyslexia

Neural network mimics the effects of stroke

Victims of stroke and other brain injuries often suffer from a peculiar dyslexia. Present them with a card bearing the word "peach," and they read "apricot." They must be able to recognize the printed word in some fashion, or else they would not come up with a related term. Yet the pathway that leads reliably from the letters on the page to their meaning and thus the name of the word has been damaged.

If such semantic errors were the only problem, understanding these patients' brain damage would be difficult enough. But the same patients almost invariably also make so-called visual errors, such as misreading "cat" for "cot." Neurologists were forced to postulate that several different areas of the brain—responsible for low-level visual as well as high-level semantic processing—were somehow almost always damaged together.

Computer scientist Geoffrey Hinton of the University of Toronto believes he has found a simpler explanation. Working with neurophysiologist Tim Shallice of the Medical Research Council's Applied Psychology Unit in Cambridge, England, Hinton built a neural network, a type of computer program that mimics some functions of the brain. Hinton's network models the processing that goes on when the brain turns letters into meaning. The collaborators found, much to their surprise, that damage to any part of the processing network will produce both visual and semantic errors.

Hinton trained his network to map combinations of letters corresponding to words into points in what he calls "semantic space"—a multidimensional set of descriptions arranged so that conceptually similar objects are close to one other. Peaches and apricots, for example, are both stone fruits, are yellow-orange in color, and have more or less fuzzy skins. Additional feedback units in the network ensure that each point in semantic space that defines a word behaves as an attractor. If network inputs result in a state near an attractor, the network will eventually stabilize there. Metaphorically, the network resembles a surface dotted with basins representing attractors; inputs roll "downhill" until they come to rest.

Once they had trained the network, Hinton and his collaborators damaged it by removing simulated neurons or destroying connections between them. Damage to the higher levels of the network—those responsible for settling on a particular attractor—caused semantic errors such as mistaking "cot" for "bed." This was easy to explain: damage changed the shape of attractors in semantic space, so that an input that would previously have settled into one basin now settled to another, nearby one.

The researchers discovered, however, that their damaged network made visual errors as well, misreading "cot" as "cat," for example. How could this be? The two words are not close in semantic space at all. The answer lies in the detailed behavior of the network and its attractors.

The input layer, Hinton explains, must map visually similar words to similar regions of semantic space—the connections are too simple to do otherwise. Even though "cat" and "cot" are far away from each other, their basins of attraction may share a common boundary. When damage to the network changes the shapes of the semantic attractors, an input that previously fell on the "cot" side of the boundary and then spiraled away toward "cot" (and "bed") may now fall on the "cat" side instead.

If damage to the higher-level parts of the network can produce both semantic and visual errors, so can damage to the input layer. Once the input lands in the wrong area of semantic space, attractors can take it anywhere, even to visually unrelated words. Indeed, Hinton says, "pretty much any damage to the network results in the same complex of errors."

Although it is too simple to mimic the full richness of the brain's woes, Hinton's network can also make more complex mistakes typical of some patients. There is the visual-then-semantic error: a human patient misreads "sympathy" as "orchestra," and the network can misread "cat" as "bed." And in cases of severe damage, the network, like a severely dyslexic person, may be unable to settle on a single word and yet still be able to say reliably whether the item in question is animal or vegetable, large or small.

Hinton is pleased that his simulated neural model has been able to capture some of the essentials of human information processing, but he maintains that the chief lesson of his work is caution. Once a system—be it a neural network, a brain or anything else—is complex enough to contain feedback loops and attractors, he says, "you just can't make obvious inferences" from symptoms to internal states. *—Paul Wallich*

Sharing Germplasm

A peace accord in the seed wars

According to one estimate, a quarter of the world's 250,000 species of edible plants may vanish in the next 50 years as habitats disappear. Many of those plants contain valuable genes that could be used to improve crops by enhancing disease resistance, improving nutritional value or increasing plants' ability to withstand environmental stress.

But the developing countries where such species are found have accused multinational companies of plundering their genetic heritage and selling it back in the form of patented seed. Meanwhile the Third World nations themselves lack the resources for conservation, and in some regions, such as the Amazon, government policies are accelerating the demise of valuable plants.

A recent agreement, however, may put an end to the acrimony of the past decade. The Global Plant Genetic Resources Initiative, which was crafted at an informal "Keystone Center" conference of governmental and nongovernmental representatives in Oslo this past summer, would boost conservation efforts. "Saving and sharing must be a common effort," says M. S. Swaminathan, who chaired the meeting and is considered the father of India's green revolution.

The key to the success of the agreement was the patent provisions. Seed companies seek strong patents to protect their investment in developing new varieties. But many Third World countries have little interest in enforcing patents. Representatives of seed companies have now agreed to market new varieties of seed in countries that lacked the means or inclination to enforce foreign patents, in return for access to valuable germplasm.

Although seed from rare plant varieties can be preserved for about $50 per year—if they are found in time—the existing international network of seed banks is acknowledged to be totally inadequate. Under the new initiative, additional seed banks would be built and grass-roots planning would revitalize monitoring and conservation efforts. At an estimated cost of $300 million per year, the program looks like a bargain, especially when it is compared with Swaminathan's estimate of $50 billion for the size of the world seed trade. The initiative will be presented to the United Nations Conference on Environment and Development next year in Rio de Janeiro. *—Tim Beardsley*

PROFILE: GERTRUDE BELLE ELION

The Satisfaction of Delayed Gratification

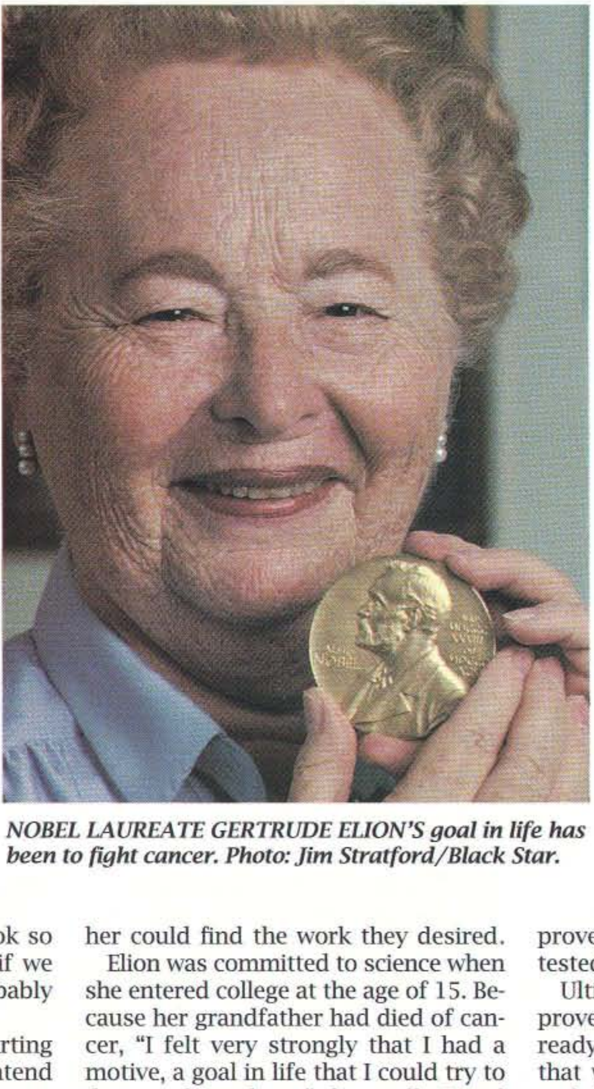
Delayed gratification does not bother Gertrude Belle Elion. She worked as a lab assistant and as a teacher, she checked vanilla bean freshness, mold content in frozen fruit, pickle acidity and the color of mayonnaise for the Quaker Maid Company, she earned her master's degree, she almost entered secretarial school and then, finally—seven years after she graduated from Hunter College in New York City—she landed what she wanted: a research job as a chemist.

Six months later Elion's division at Johnson & Johnson closed, and she was offered a new position testing the tensile strength of sutures. "I said I didn't think that was what I wanted to do, thank you very much," the red-haired Elion recalls in a muted but feisty Bronx accent. "So I went looking again."

Elion was as persistent and patient with the drugs that she elucidated over the next 40 years as she was at finding the right job. When Elion joined the Wellcome Research Laboratories in 1944 (shortly after shunning suture-stretching), she began to study nucleic acid metabolism. Her work, and that of her colleague George H. Hitchings, with whom she shared the Nobel Prize in Physiology or Medicine in 1988, led to the development of novel compounds to combat leukemia, organ transplant rejection, malaria, gout and herpesvirus.

The innovative drugs were discovered one slow step after another. "Maybe it was more exciting that way, to find things out a little at a time," Elion muses. "On the other hand, it took so long to get things done, I think if we were starting now we would probably do what we did in 10 years."

If Elion herself were just starting out, she would not have to contend with some of the hurdles facing women in the 1930s and 1940s. Few research positions were open to women, and Elion was even told in one interview that she would be a distracting influence. "It surprises me to this day that I didn't get angry. I got very discouraged," Elion says. "But how could I say, 'No, I won't be a distracting influence'? How do I know what the men were like?" She laughs and points over her shoulder to a black-and-white photograph of herself taken just after she joined Wellcome: "I wasn't bad-looking, I was kind of cute." It was only when World War II pulled men out of their jobs that Elion and women like her could find the work they desired.



NOBEL LAUREATE GERTRUDE ELION'S goal in life has been to fight cancer. Photo: Jim Stratford/Black Star.

Elion was committed to science when she entered college at the age of 15. Because her grandfather had died of cancer, "I felt very strongly that I had a motive, a goal in life that I could try to do something about," she recalls. Faced with a choice between biology and chemistry, Elion says she purposefully chose the discipline that did not involve dissection. Although her father, a dentist, wanted Elion and her brother to pursue his profession ("neither one of us was keen on dentistry"), her parents supported her choice. Elion lived at home while she worked and completed her master's at New York University.

By chance, some of the first compounds that she studied at Wellcome were used for the treatment of cancer. Under Hitchings's leadership, the laboratory examined the possibility of selectively blocking nucleic acid synthesis. Although James Watson and Francis Crick had not yet discovered the double helix, scientists knew that DNA was the principal component of genetic material.

Following a contemporary theory—the antimetabolite theory—Hitchings hoped to interfere with nucleic acid metabolism in such a way as to kill bacteria or tumor cells but to leave healthy cells intact. The idea was to slightly alter a compound routinely used by a dividing cell, to fool the unwanted organisms into incorporating the imposter and to hope for devastating consequences. Hitchings and Elion were able to demonstrate that tumor cells, bacteria and viruses metabolized nucleic acid analogues differently—a clue vital to chemotherapy.

Elion was among the first researchers to work on purines, one of two main categories of nucleic acids. The laboratory found several compounds that could antagonize, or block, the synthesis of certain nucleic acids in bacteria. In collaboration with the Sloan-Kettering Institute for Cancer Research, Elion sent the compounds off to be tested for their ability to stem mouse tumor growth. One of the drugs, diaminopurine, proved so effective that it was soon tested in leukemic patients.

Ultimately the toxicity of the drug proved to be too high, but Elion was already probing the metabolic pathways that were inhibited by diaminopurine and found several other compounds that interfered with purine metabolism. One, 6-MP (for 6-mercaptopurine), was tested in children with acute leukemia. It was rapidly approved by the Food and Drug Administration in 1953, just two years after it had been synthesized. Although the children survived only a year or so longer with the drug, the field of cancer chemotherapy had been revolutionized. The treatment is still used today. "I think the thing we take a lot of pride in is the fact that our compounds have solved real medical problems. They haven't been just me-too compounds," Elion says.

The success of the drug also allowed Elion to stop worrying about not having a Ph.D. "In my mind, it was a big deal up until 6-MP," she says. A few years before, she had to decide between her job and getting her doctorate and had chosen, not without heartache, to stay at the lab. But, she says, chuckling and pulling bulky bound volumes of papers off a shelf and stacking them on the table, she published "much more than a thesis would have been."

Just after 6-MP was approved for the treatment of leukemia, Robert Schwartz of the New England Medical Center found that the drug blocked antibody formation in rabbits. So a British transplant surgeon, Roy Y. Calne, decided to test 6-MP's effectiveness in preventing organ transplant rejection in animals. The pivotal test of 6-MP almost never took place. Calne intended to evaluate the drug with a colleague of his, Kenneth Porter. Porter went away on vacation, came back and tried 6-MP on skin transplants in mice. He soon called Calne to tell him the compound was ineffective. Calne, however, had just finished treating dogs receiving kidney transplants with 6-MP. "And Roy says, 'I've got news for you, it does [work],'" Elion crows. "Now that kind of happenstance gives you the shudders."

Elion and Hitchings later conferred with Calne and suggested he try a compound closely related to 6-MP, azathioprine. This drug, which preceded cyclosporine by 16 years, is still widely used to prevent organ transplant rejection. Another purine analogue revealed a treatment for gout and, much later, for leishmaniasis, a parasitic disease that is widespread in India and the Middle East.

Understanding the mechanisms of each new compound led Elion to novel drugs: she would use the characteristics of one as a probe to discover the next. "You were essentially feeling your way by making this group a little larger," Elion observes. She shapes her compounds as she talks about them. Her hands substitute a sulfur here, a nitrogen there and an oxygen back here: "No, that makes it worse. Putting one on here—no, that too makes it worse."

Elion and her colleagues could not "see" the enzymes that they were describing; indeed, many of the enzymes were yet to be identified. Still, when X-ray crystallography made enzyme structures available, the antagonists that they had picked the hard way turned out to be the right ones.

Although her work was creative exploration, Elion says she would always consider its practical application. Indeed, a cartoon at the lab recently depicted Elion asking, "And what would you do with the information when you get it?" When research reached a dead end, Elion was able to let it go.

Very often, however, she would go back later and pick something up again. One of her biggest discoveries resulted from such a revisit. In the late 1960s there was little hope of treating viral diseases and not much enthusiasm about engaging in such research. Yet Elion was inspired. Before diaminopurine was rejected as a leukemic treatment in the 1950s, it had also shown some antiviral activity. But the compound's toxicity had been too great, and the laboratory had become quickly immersed in cancer chemotherapy. Then, in 1968, it was reported that a purine nucleoside, called adenine arabinoside, had antiviral promise.

"We take a lot of pride in... the fact that our compounds have solved real medical problems."

"That just reawakened me," Elion remembers. "And I thought if adenine, then why not diaminopurine?" She tested diaminopurine closely, sending related compounds across the Atlantic to the Wellcome lab in England to be evaluated in animals for their effectiveness. "I used to get my results in the form of telegrams. They'd get excited and send back: 'Oh yeah, this is great, will you send some more?'" describes Elion, becoming elated all over again.

The quest led to the development of an acyclic, or opened chain, purine nucleoside—better known as acyclovir, which is used to treat herpesvirus infections. The drug unleashed a flood of similar compounds. "You couldn't believe how fast people jumped into making these acyclic nucleosides," Elion says.

Based on her work with antiviral drugs, Elion's lab proceeded to discover AZT after she retired in 1983. Although she is often credited with direct involvement in the development of the drug, she demurs. "The only thing I can claim is training people in the methodology: how to delve into how things work and why they don't work and what resistance is, and so on. The work was all theirs." To Elion, antiviral research remains one of the most interesting fields in science today.

Three years ago Elion was awakened at 6:30 in the morning by what she first thought was a prank call to learn that she and Hitchings had won the Nobel Prize. (They shared the honor with Sir James W. Black, who developed the first clinically useful drug to block beta receptors.) Nobel paraphernalia cover her office, but Elion is circumspect about the honor. She says she has repeatedly been asked whether the Nobel was the pinnacle of her career, the thing she had strived most for. "Of course not," she exclaims. "Why would you? That's a silly motivation. We had our reward with all our drugs, and this is very nice, but you don't work for this. I mean if you didn't get it, you would have wasted your whole life!"

This year Elion received another honor, becoming the first woman to join Thomas A. Edison and George Washington Carver in the National Inventors Hall of Fame. Her induction surprised her, she says, because researchers describe finding drugs as discovery not invention. "But I guess I had invented new compounds—and then had to discover what they were good for." As for being the first woman in the Hall, Elion says it was high time.

One honor, however, came late for her. The National Academy of Sciences did not offer membership to Elion, who is now 73 years old, until she won the Nobel Prize. She accepted and was inducted last year.

Although Elion hoped that retirement would provide her with more time to work in the lab, she finds she is too busy traveling, writing and lecturing. And she has rediscovered teaching. For the past six years, Elion has worked with students at Duke University Medical School. But Elion believes students need to be inspired long before they reach graduate school or college.

She describes with delight the curiosity of eight- and nine-year-olds: "They love to discover. If you can just keep them at it and make them realize what it is like, they will go into science." Recently Elion met with high school students. "They don't realize what they did for me. I couldn't sleep, I got so excited talking to them," Elion says. "And as I left that evening, a black girl, half my size, waved and said, 'I'm going to do it, too,' and I said, 'Of course you are.'" —*Marguerite Holloway*

SCIENCE/SCOPE®

Vital to the defense of coalition forces in Operation Desert Storm were two Hughes Aicraft Company missiles, the Maverick and the TOW. The U.S. Air Force fired approximately 100 Maverick missiles per day, while Saudi forces relied heavily on TOW missiles to clear Khafji of invading Iraqi troops, destroying 46 armored vehicles. TOWs were also fired from Marine Corps Cobra helicopters during the Khafji battle, helping destroy 20 T-55 Iraqi tanks and armored personnel carriers. The Mavericks and TOWs were two of 55 different Hughes systems deployed to the Persian Gulf during Operation Desert Storm.

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Iron Deficiency

One of the most common health problems worldwide and potentially one of the most treatable, iron deficiency can have devastating effects. It can jeopardize a child's mental and physical development

by Nevin S. Scrimshaw

Iron deficiency is the most prevalent nutritional problem in the world today. Two thirds of children and women of childbearing age in most developing nations are estimated to suffer from iron deficiency; one third of them have the more severe form of the disorder, anemia. Furthermore, unlike classical nutritional diseases—such as vitamin A deficiency, which can lead to blindness, and iodine deficiency, which can cause retardation and deafness—iron deficiency is found in all societies, developing and industrial alike. In the U.S., Japan and Europe, for instance, between 10 and 20 percent of women of childbearing age are anemic.

Iron deficiency commonly remains unrecognized. Because of subtle symptoms such as pallor, listlessness and fatigue, the disorder is not regarded as life-threatening. Yet iron deficiency can have a multitude of effects—and can even result in death.

NEVIN S. SCRIMSHAW is director of the Food, Nutrition and Human Development Program for the United Nations University in Tokyo and Institute Professor Emeritus at the Massachusetts Institute of Technology. In 1949 he became the founding director of the Institute of Nutrition of Central America and Panama, where he worked to combat iodine deficiency and kwashiorkor. Scrimshaw is particularly interested in the relation between infection and nutrition and has sought to help countries attain nutritional self-sufficiency. A member of the National Academy of Sciences, earlier this year he won the Alan Feinstein Hunger Award for Research and Training and the World Food Prize. Scrimshaw enjoys skiing, gardening and writing at his overgrown farm in the White Mountains of New Hampshire.

In the past several years researchers have found that iron deficiency is associated with the often irreversible impairment of a child's learning ability and other behavioral abnormalities. Although the neurochemical roles of iron are not fully understood, it is clear that low levels of the nutrient can have a significant adverse impact on brain function. In addition, diminished levels of iron in adults can affect work capacity and productivity and, by impairing the immune system, increase the chances of acquiring and dying from infection.

Despite the possibilities for low-cost intervention, many countries lack an effective system for diagnosing, treating and preventing iron deficiency. Consequently, progress in combating iron deficiency has been slight. Whereas the administration of effective treatments for deficiency in vitamin A and in iodine can be made uniform in nearly all countries, therapies for iron deficiency must be tailored to suit individual cultures and countries.

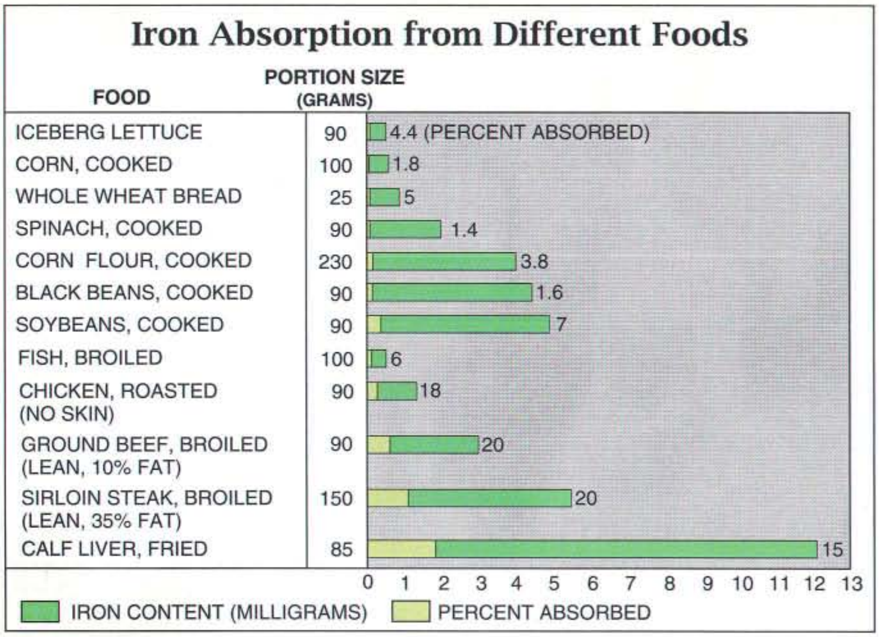
The situation could soon improve. This year a United Nations subcommittee on nutrition established a working group to promote the control of iron deficiency. The group is collaborating with the World Health Organization (WHO) in developing a 10-year plan to eliminate this public health scourge. Understanding the multiple functional consequences of iron deficiency is crucial to that effort.

Iron has diverse biological functions, and it is this diversity that accounts for the wide-ranging impact of its deficiency. The metal is best known for its role in the transport of oxygen in blood. As a component of hemoglobin, iron helps the molecule pick up oxygen in the lungs and shuttle and release it throughout the body. Approximately 73 percent of the body's iron is found in hemoglobin, where it is constantly recycled as more red blood cells are created.

Of the balance of the body's iron, 12 to 17 percent is stored in two molecules—ferritin and hemosiderin—both of which can bind large numbers of iron atoms. (Each molecule of ferritin alone binds 4,500 iron atoms.) Myoglobin accounts for another 15 percent of the iron, acting as a reservoir of oxygen for muscle cells. A small but extremely important amount (0.2 percent) of body iron is bound to transferrin, a compound that shuttles iron from sites of release to sites of need. Lactoferrin—a compound found in breast milk, mucosal tissues and white blood cells, or leukocytes—also binds a percentage of the body's iron so that it is not available for bacterial growth, thereby stemming infection.

The minute amount of iron not accounted for by these compounds is found in myriad enzymes crucial to metabolism. These enzymes include oxidases, catalases, reductases, peroxidases and dehydrogenases. Each enzyme

GUATEMALAN WOMAN and boy sell fruit in a marketplace in the highlands. Iron deficiency is often caused by the predominantly vegetarian diets common to most developing nations.



plays an important role as a reversible donor or acceptor of electrons during cellular metabolism.

All the iron needed to execute these diverse tasks comes from diet. Although vegetables, particularly spinach, are regarded as impressive sources of iron, plant (nonheme) iron is relatively poorly absorbed. For instance, only 1.4 percent of the iron from spinach can be taken in by the body; other vegetables yield slightly more: 1.6 percent from black beans, 4.4 percent from lettuce and 7 percent from soybeans.

In contrast, 20 percent of iron from red meat, in the form of heme iron, can be absorbed. Iron from poultry, fish and breast milk is equally well assimilated, but the concentrations are lower. The composition of a meal can influence the amount of iron that is retained. For example, if a meal contains both heme and nonheme iron, the former will improve the absorption of the latter. Vitamin C enhances the utilization of nonheme iron, but substances like tannin from tea as well as fiber and phytates from plants inhibit it. Absorption also changes in accordance with the amount of iron in the body: it decreases if individuals are iron replete and increases if they are iron deficient.

Poor absorption from the predominantly vegetarian diets of most people in developing countries is a primary cause of iron deficiency. For the poor, meat is expensive and consumed in small quantities or not at all. Iron deficiency and anemia affect the majority of individuals in such populations.

Iron deficiency is not caused by dietary imbalances alone—it can occur even when the diet has adequate iron. Other culprits are chronic blood loss caused by hookworm and schistosomiasis and the excessive storage of iron as hemosiderin, a result of malaria. Abnormal uterine bleeding is another cause.

Hookworm eggs from human feces hatch on moist soil to produce tiny larvae that painlessly enter the skin of the feet. The bloodstream and lymph vessels then carry these larvae to the lungs. From there they find their way into the trachea, or windpipe, to the pharynx and, ultimately, to the small intestine after they are swallowed. They bind to the intestinal lining and secrete an anticoagulant that causes bleeding proportional to the number of worms. As many as three million worms may be recovered after severe cases are treated.

Hookworm rarely kills its victims, but it can leave them weak and listless. Children with hookworm disease are not only pale and anemic but slow and dull. Indeed, the parasite was largely responsible for the image of laziness of poor Southern whites in the U.S. Because poor whites formed the bulk of the Confederate Army during the Civil War, some scholars have suggested that hookworm disease was a significant factor in the army's defeat by the North.

Although hookworm has been largely eradicated in the U.S. and other industrialized nations, it continues to plague over 900 million people—more than one fifth of the world's population. Schistosomiasis afflicts more than 200 million people, and malaria causes 200 to 300 million deaths every year.

Shortages of iron, whether caused by disease or diet, or both, are described in three overlapping stages, beginning as deficiency and culminating as anemia. (There are many additional causes for anemia, including genetic defects and other nutritional disorders.) Although anemia is the more severe condition, the impairment of many bodily functions, such as harmful changes in biochemistry and in the effectiveness of important iron-containing enzymes, occurs long before anemia sets in.

In the first stage, stored iron is depleted, a process reflected in declining levels of ferritin. Next, levels of serum iron plummet, and as a result the iron transport protein, transferrin, is no longer fully saturated. At this second stage, cellular compounds requiring iron begin to be affected. As the deficiency persists, the synthesis of hemoglobin is inhibited, and anemia develops. This last stage is characterized by reduced numbers of now small, pale blood cells.

One of the more devastating consequences of iron deficiency and anemia has been elucidated over the past 15 years, although it is far from clearly understood. Anemic children and adults have often been described as backward or apathetic, but these behavioral aspects were historically attributed to the lack of oxygen transported in the blood. Recently remarkable advances in probing the relation between iron status and cognition have illuminated these symptoms.

Although there were a number of early studies in animals, it was not until 1973 that Frank A. Oski of Johns Hopkins University School of Medicine and his colleagues at Syracuse University reported that anemic infants improved their performance on certain behavioral tests after a single large injection of iron. The tests, called the Bayley Scales of Infant Development, measure a broad range of activities, including motor skills, affective responses and attention span, as well as general cognitive function. Five years later Oski and Alice S. Honig, also at Syracuse, found similar improvements after such treatment in anemic infants when compared with normal infants who received the same treatment.

In 1982 Ernesto Pollitt of the University of California at Davis provided the first demonstration of the adverse effects of subclinical iron deficiency as opposed to anemia. Pollitt, then at the Massachusetts Institute of Technology, found that three- to six-year-olds in Cambridge, Mass., who were mildly iron deficient had poorer scores on a battery of behavioral tests than did preschoolers whose iron status was normal. He then showed that the scores significantly improved after 11 to 12 weeks of iron therapy.

Pollitt repeated these studies with both iron-deficient and anemic preschool children in Egypt, Guatemala and Indonesia. This time he found only limited improvement in the Guatemalan and Egyptian children, even when their blood levels of iron returned to normal. Only the Indonesian children, who were from a town near Bandung, did significantly better on the test after iron supplementation, presumably because their deficiency was less severe. Other researchers have found the same irreversibility during double-blind studies in Costa Rica, Chile and various parts of Guatemala.

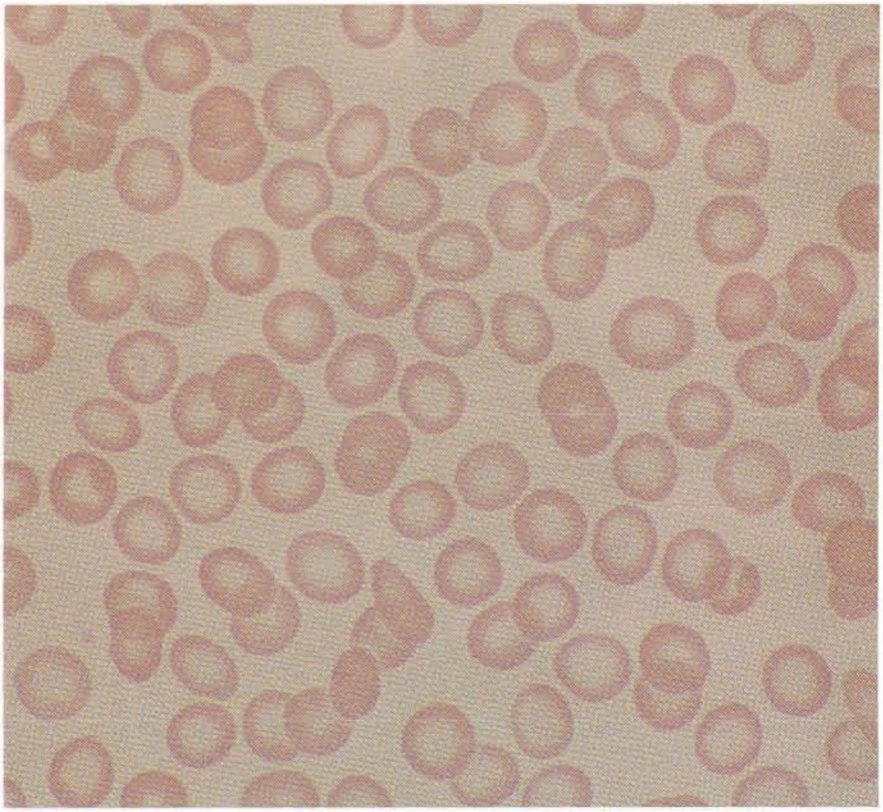
The adverse effects of iron deficiency on cognitive performance also proved irreversible in a study of 2,000 children in Thailand. There, Pollitt and his collaborators found a significant correlation between iron levels, IQ and a Thai language achievement test: the higher the iron levels, the better the scores. Studies in other parts of the world, including India, Papua New Guinea and Semerang in Indonesia, have consistently found a similar association.

Apparently iron deficiency is educationally deleterious regardless of ethnicity or physical or social environment. The lack of recovery in many children after iron supplementation underscores the importance of preventing iron deficiency.

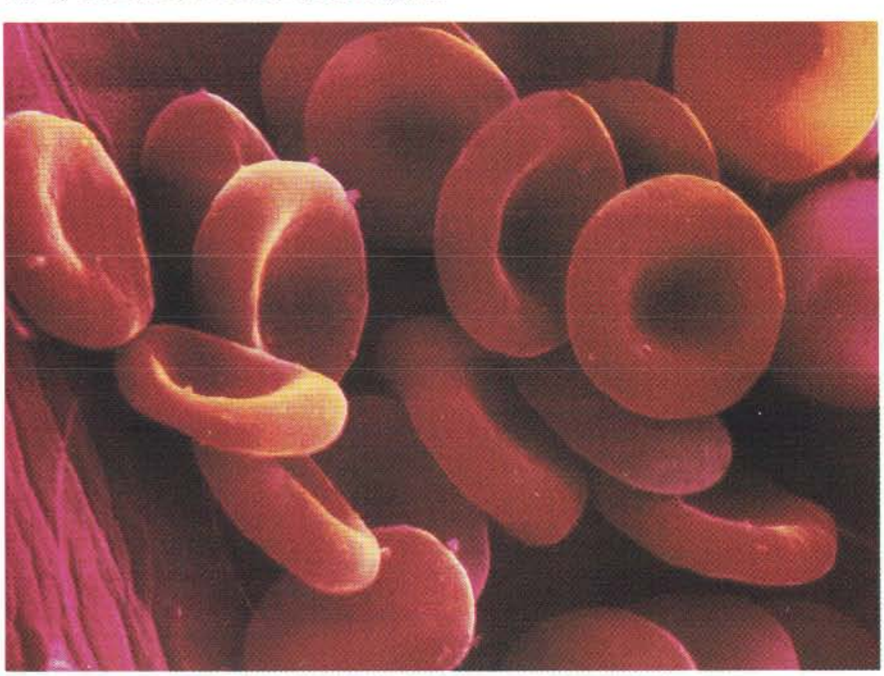
A possible neurochemical basis for these problems has recently been suggested. Moussa B. H. Youdim of the Technion Medical School in Haifa and Shlomo Yehuda at Bar-Ilan University in Ramat-Gan, Israel, found that rats with low levels of iron had fewer D_2 receptors—one of several families of dopamine receptors—in certain regions of the brain. These findings suggest that iron is important to the normal development and functioning of dopaminergic neurons and that early changes could lead to permanent damage.

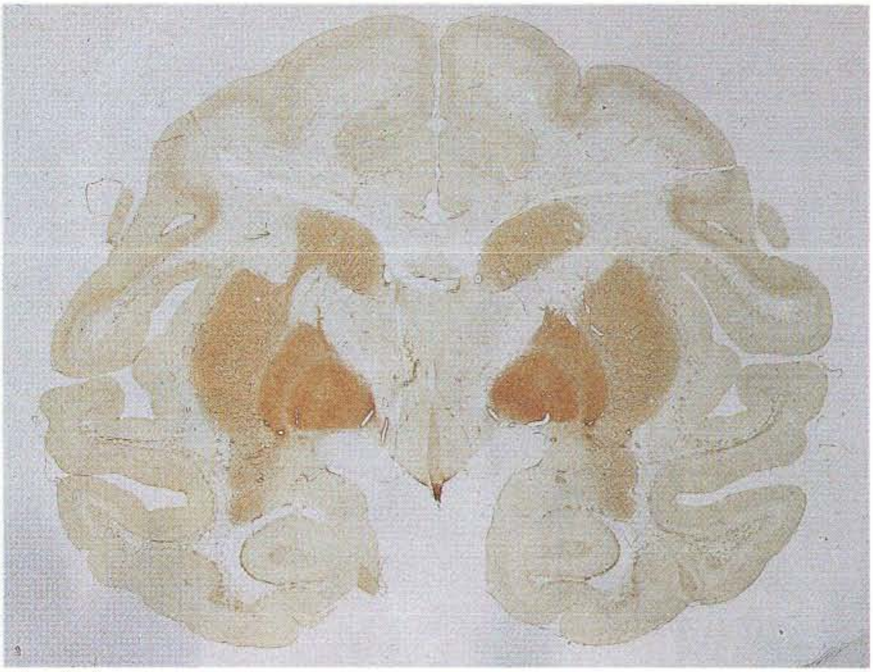
The precise role of iron in the brain, however, has not been determined. The nutrient is distributed quite unevenly but appears to reflect the location of certain neurons that release the neurotransmitter gamma-aminobutyric acid, or GABA [*see illustration on next page*]. The release of GABA inhibits neuronal transmission. It is also noteworthy that iron is found in monoamine oxidase, an enzyme vital to the production of a host of neurotransmitters, including serotonin, norepinephrine and epinephrine as well as dopamine. Thus, there are tantalizing indications of how iron deficiency might affect the central nervous system.

Behavioral changes caused by iron deficiency are not found solely in infants and young children. Physicians visiting developing countries have repeatedly demonstrated a connection between iron levels and work capacity and productivity in adults. In 1970 I found that certain laborers on Guatemalan sugar and coffee plantations performed poorly on the Harvard Step Test (HST), which requires that they step up on and then down off a bench every two seconds for a maximum of five minutes, if pos-



ANEMIC RED BLOOD CELLS are paler and smaller (*above*) than robust erythrocytes (*below*). By limiting the production of hemoglobin, the shortage of iron impairs the ability of these cells to transport oxygen.





RHESUS MONKEY BRAIN shows the presence of iron in the darkly stained areas. The location of the nutrient reflects the termination sites of a class of neurons that produce gamma-aminobutyric acid (GABA). Researchers believe low levels of iron may interfere with degradation of GABA or may impair the performance of dopamine-producing neurons. Photograph courtesy of Joanna M. Hill of the National Institutes of Health.

sible. All these workers, considered lethargic and stupid by the plantation owner, proved to be anemic.

My observation was confirmed by Fernando E. Viteri of the University of California at Berkeley. Earlier studies in animals had shown an association between poor performance on a treadmill and low hemoglobin levels. Viteri, then at the Institute of Nutrition of Central America and Panama, saw the same correlation in Guatemalan laborers. After treatment with iron, the subjects' HST results improved remarkably. Coincidentally, Samir S. Basta, who was then my graduate student at M.I.T., made similar discoveries among road construction workers and rubber tappers in Indonesia.

A question remained: Did these differences in physical capacity have any effect on the laborers' productivity? Basta, who is now director of UNICEF in Europe, established a strong correlation between hemoglobin levels, HST results and the amount of rubber the Indonesian tappers collected. He determined that anemic tappers who were given iron supplements for 60 days augmented their take-home pay by 30 percent. Iron supplementation also increased the productivity of tea pickers in Indonesia and Sri Lanka and of laborers in Kenya and Colombia.

One of Basta's observations suggested the mechanism by which iron depletion hindered performance. He discovered that both the road construction workers and the tappers were better able to work after only 30 days of iron supplementation—before there was any significant increase in hemoglobin. It became clear that iron depletion did not solely affect oxygen transport in the blood but also interfered with oxygen exchange in muscles. Indeed, blood transfusions that restored hemoglobin levels to normal in anemic tea pickers in Sri Lanka failed to improve their treadmill performance: further evidence that the oxygen-carrying capacity of blood is not the single culprit.

Studies in animals further clarified some of the biochemical mechanisms at work in muscles. For example, iron-deficient rats were found to have lower levels of such important proteins as myoglobin, cytochromes and mitochondrial and other oxidative enzymes. Human studies are still lacking, in part because it is inconvenient to take biopsies of muscles.

In addition to reducing the ability of premenopausal women to perform work, iron deficiency curtails their ability to successfully produce and raise healthy children. In many underprivileged populations the limited availability of iron in the diet and the pathological losses associated with parasites increase the likelihood that a woman will experience iron deficiency. Already struggling with poverty and the demands of procuring and preparing food, maintaining a home and caring for a family, many such women are jeopardizing their own health and that of their fetuses.

Although the shortage of iron affects both sexes, women are particularly at risk. Normally men lose only one milligram of iron every day through urine, skin and feces, an amount easily replenished. Such losses are proportionally less in women because of their smaller body size: only about 0.7 to 0.8 milligram a day.

Over the course of a month, however, women lose far greater amounts than men. Menstrual bleeding causes an additional average daily loss of 0.4 to 0.5 milligram, and 10 percent of women lose three times that amount. Intrauterine devices can lead to even more bleeding. Although menstruation ceases during pregnancy, women lose iron to the placenta and to the fetus—roughly five milligrams a day during the second and third trimesters, or a total of 370 milligrams by delivery. This loss is compounded by blood lost during and after delivery.

Iron deficiency during pregnancy can prove dangerous. Maternal mortality, prenatal and perinatal infant death and prematurity are significantly increased. If the mother is iron deficient while she is pregnant, the child is born with poor iron reserves and is at greater risk of morbidity, mortality and learning disorders. Low-birth-weight babies exhaust their iron stores at an earlier age than do normal infants, and they soon require more iron than breast milk can supply.

Treatment works—if it reaches the child in time. In studies in Indonesia, children receiving iron grew more than did those receiving placebo. (Studies of this kind receive ethical approval if they are designed to determine the need for iron supplementation and if, after it is determined that such therapy is effective, the placebo group is also given iron until hemoglobin levels become normal.) The results suggest that iron either has a direct metabolic effect on the child or exerts an indirect effect by increasing appetite, a known boon of iron therapy in people of all ages.

Iron supplementation may also help children by reducing the severity or incidence of infection. Malnutrition in any form is likely to decrease resistance to infection, and nutritional deficiencies are ubiquitous among underprivileged populations. Still, iron deficiency remains the most common, and it is clearly associated with increased illness resulting from infection.

As early as 1928, British physicians reported that bronchitis and gastroenteritis were more likely to develop in poorly nourished infants than in well babies. When malnourished infants received iron supplementation, the incidence of these diseases decreased.

Almost 40 years later the first controlled study of iron and morbidity was published. Morten B. Andelman and Bernard R. Sered of the Chicago Board of Health studied more than 1,000 infants from poor Illinois families. One group received a formula containing vitamins but no iron; the other group received formula with vitamins and iron. The results were striking: the second group had half as many respiratory infections as the first.

Similar findings were reported in Alaska by the wife-and-husband team of Carolyn and Robert Brown of the U.S. Public Health Service. They found a direct correlation between low hemoglobin levels and the prevalence of diarrheal and respiratory diseases in native Alaskan children. Another researcher, Robert Fortuine, also with the U.S. Public Health Service in Alaska, found that meningitis in anemic children often proved deadly, whereas the disease did not prove fatal in any of the nonanemic children he studied.

Although knowledge of the mechanisms by which iron deficiency results in increased morbidity is far from complete, both animal and human studies offer clues. Raymond B. Baggs, a graduate student at M.I.T., fed rats progressively less iron and simultaneously infected the animals with salmonella, a bacterium that causes diarrhea. He found that as the amount of iron in the animals' diet declined, the incidence of morbidity and mortality from the infection rose.

To kill bacteria, white blood cells sharply increase oxygen consumption, a process called respiratory burst. Respiratory burst, in turn, produces an oxygen radical, peroxide. Baggs searched for the cause of the findings and discovered that although white blood cells in the gastrointestinal tract of iron-deficient animals could engulf bacteria, the cells had low levels of the iron-dependent enzyme myeloperoxidase. Without this enzyme, a cell cannot create the free oxygen radicals needed to kill the ingested bacteria.

In studies in Indian children, Ranjit K. Chandra, now at the Memorial University of Newfoundland, showed that respiratory burst diminishes as levels of transferrin fall. At the same time, there is an increase in the number of surviving bacteria in lymphocytes infected in vitro and a fall in the production of new lymphocytes, also in vitro.

Other researchers in India have shown that as the amount of serum transferrin falls, the capacity of tuberculosis patients to respond to a skin test gradually disappears. This failure could result either from the protein deficiency responsible for the decrease in transferrin or from the associated decline in serum iron. This type of response, referred to as delayed cutaneous hypersensitivity, is an important indicator of the health of the cell-mediated immune system.

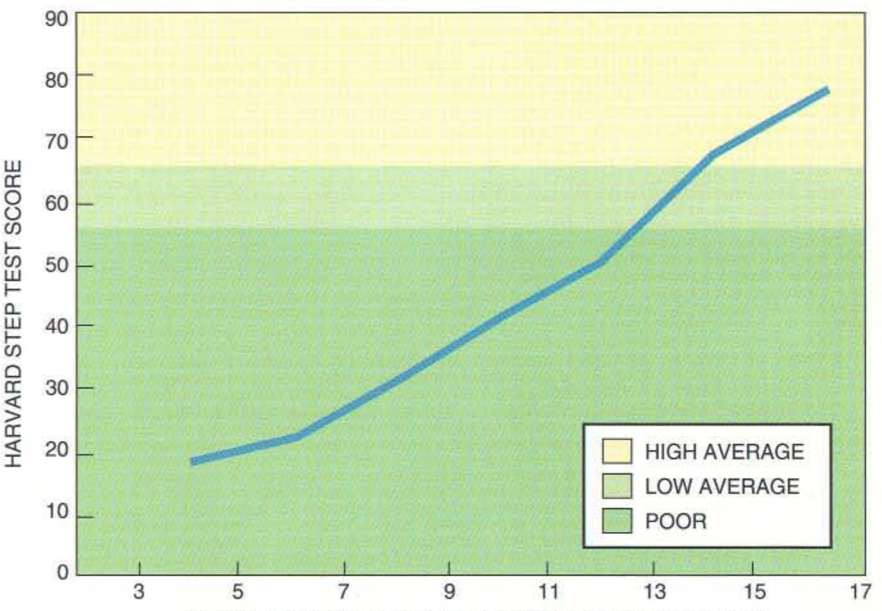
Another little-known consequence of iron deficiency was discovered by chance during a study of behavioral changes in iron-deficient children. Oski noticed that the blood levels and the urinary excretion of epinephrine were much higher in his subjects than in normal children. In 1975 he speculated that his finding was related to the behavioral changes he had observed. It is common for animal studies to point to the need for confirmatory investigations in human subjects, but in this case the opposite occurred.

Three years later Erick Dillman of the Institute of Nutrition in the Hospital for Nutritional Diseases in Mexico City and a group of collaborators at the University of Washington decided to explore Oski's findings, this time using rats. They discovered that iron-deficient rats were unable to maintain a normal body temperature when exposed to cold. In these rats, oxygen consumption was also reduced, indicating a lower metabolic rate and therefore less heat production. In addition to epinephrine, the hormone thyroxine, which is secreted by the thyroid gland and which regulates metabolic rates, was abnormally high in the rats' urine.

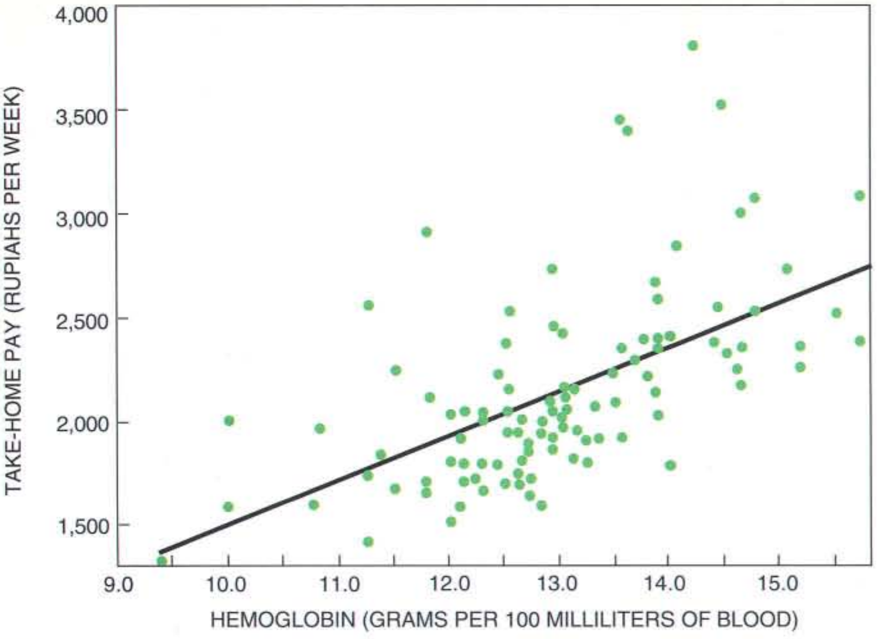
Miguel Layrisse of the Institute of Scientific Investigations in Caracas, Venezuela, learned of these results and decided to investigate further. He placed anemic and nonanemic men in a water tank under conditions in which blood pressure, body temperature and oxygen consumption could be monitored and periodic blood samples obtained. The water in the tank was held at body temperature (37 degrees Celsius) for one hour and then lowered to 28 degrees C.

Layrisse's findings paralleled Dillman's. Five subjects with severe iron deficiency proved unable to maintain their body temperature. Moreover, oxygen consumption decreased and epinephrine levels in urine increased in individuals with mild as well as severe iron deficiency. When they were given 60 milligrams of iron three times a day for seven days, oxygen consumption returned to normal, even though there was not time enough for the hemoglobin levels to change significantly. The observation that iron deficiency lowers resistance to cold exposure and that this phenomenon is reversible may be particularly significant for those anemic elderly who are already more susceptible to cold because of less subcutaneous fat or poor circulation.

Despite the clear advantage of iron



WORK PERFORMANCE has been linked to the level of iron in the blood. Anemic Guatemalan laborers performed poorly on a physical test (the Harvard Step Test), whereas those with higher hemoglobin levels performed well.



PRODUCTIVITY of Indonesian rubber tappers varies with hemoglobin levels. The diagonal line marks the association between income and hemoglobin.

supplementation in restoring temperature regulation or counteracting reduced work capacity, treating iron deficiency is not as straightforward as treating some other nutritional disorders. For example, in iodine deficiency, iodine is easily supplied by iodized salt and, unlike iron, is not harmful in large amounts. The same is true for vitamin A deficiency: a dosage of 300,000 international units every four to six months is safe and effective.

Iron supplementation at a level not exceeding 100 milligrams of ferrous sulfate daily is beneficial for normal individuals who are deficient because of poor absorption of dietary iron and the effects of parasites and other infections. Most populations can also benefit from a staple food fortified with somewhat less iron—for example, cereals, bread, sugar, salt and even monosodium glutamate. Yet the fortification of multiple dietary sources for a population should be avoided.

The old adage that too much of a good thing is no longer good is particularly relevant to iron supplementation. One of the first insights into the dangers of iron excess was provided by South African Bantu men, who have a high incidence of a serious liver disease called hemochromatosis. In this disease the liver is characterized by the excessive accumulation of iron, the development of fibrous tissue and often the occurrence of fatal cancer.

Investigation revealed that the individuals affected were, and still are, accustomed to consuming large quantities of beer fermented locally in iron pots. Because the acid of fermentation leaches iron into the beer and because the quantities consumed daily are very large, toxic iron overloads develop. Obviously these circumstances are unusual, but they have also been reported in a number of other African countries. (Hemochromatosis can also develop in individuals who have a relatively rare genetic defect that destroys the person's ability to modulate the absorption of iron in response to need.)

In 1970 Hylton McFarlane of Manchester University in England reported from South Africa that intramuscular injections of iron given to severely malnourished children to correct their anemia were associated with fatal infections. Reports from Nigeria, New Guinea and Somalia have also indicated that iron injections exacerbate malaria.

The reason for such a result is that iron is valuable not only to the individual but also to the organism infecting that individual. Usually the body has several mechanisms for withholding iron as part of its resistance to such infections. When white blood cells disintegrate after ingesting and killing bacteria and viruses, they release interleukin-1, whose many functions include stimulating the synthesis of ferritin, the efficient iron storage protein. Ferritin production ensures that the iron released from decaying red blood cells will not be available to invading organisms. Disintegrating leukocytes will also discharge lactoferrin at sites of inflammation. Lactoferrin binds iron more strongly than can infecting organisms.

There is little doubt that the body's methods of withholding the iron needed by microorganisms for their multiplication constitute an important way of reducing the virulence of bacterial and protozoan infections. (These mechanisms have been extensively reviewed by Eugene D. Weinberg of Indiana University.) In the presence of too much iron, however, these protective mechanisms are overwhelmed and ineffective.

This complication does not mean that iron deficiency is ever a desirable state. It does mean, however, that giving malnourished individuals large doses of iron is potentially dangerous. Particular care must be taken so that individuals whose cell-mediated immunity has been compromised by iron deficiency do not become overwhelmed by infection before recovery of immunity can occur. Modest daily amounts of iron contribute to a healthy immune system without weakening the protective mechanisms that withhold iron from microorganisms.

The serious consequences of iron deficiency for human health, behavior and performance and the wide prevalence of this disorder are urgent reasons for the strong national and international efforts to curb this illness. Both UNICEF and WHO will need to coordinate strategies for fortifying appropriate foods with iron and providing iron supplements to vulnerable groups. At the same time, infections must be prevented, particularly those causing blood loss, such as hookworm, schistosomiasis and malaria. With concerted international effort, iron deficiency, and the unacceptable suffering it causes so many people around the world, could become another of the major public health problems eliminated in this century.

FURTHER READING

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GASPARDONE

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GRUPPO

Fullerenes

These cagelike molecules constitute the third form of pure carbon (the other two are diamond and graphite). C_{60}, the archetype, is the roundest molecule that can possibly exist

by Robert F. Curl and Richard E. Smalley

In May of 1990 Wolfgang Krätschmer and his student Konstantinos Fostiropoulos carefully mixed a few drops of benzene with a specially prepared carbon soot. The clear solvent turned red.

Excitedly, the two workers for the Max Planck Institute for Nuclear Physics in Heidelberg telephoned their collaborators, Donald Huffman and Lowell Lamb of the University of Arizona in Tucson, who quickly repeated the experiment. The excitement continued as the two groups communicated daily by telephone and fax, exchanging measurements of the material—its infrared and ultraviolet spectra, its X-ray diffraction pattern and its mass spectrograph. Yes, the values all matched those predicted for the 60-atom carbon cluster buckminsterfullerene.

Even though some theorists had argued that this hollow, soccerball-shaped molecule should be detectable in abundance in such everyday circumstances as a candle flame, the German-American team had actually found it, succeeding where all others had failed. They were the first to observe this roundest of all round molecules, and they knew that chemistry books and encyclopedias would never be quite the same. Now there were three known forms of pure carbon: the network solids, diamond and graphite, and a new class of discrete molecules—the fullerenes.

When we heard of this breakthrough a few months later in Texas, we celebrated, with champagne all around. For although we had to some extent been scooped, we had been vindicated as well. Five years earlier we had had our own Eureka! experience. Together with our colleague Harold W. Kroto of the University of Sussex and our students James R. Heath and Sean C. O'Brien, we had found that C_{60} could be made in a uniquely stable form simply by laser-vaporizing graphite in a pulsed jet of helium. We had gone on to propose that this extraordinary stability could be explained by a molecular structure having the perfect symmetry of a soccerball. Because the architectural principle also underlies the geodesic dome invented by the American engineer and philosopher R. Buckminster Fuller, we named it buckminsterfullerene, or buckyball for short.

ROBERT F. CURL and RICHARD E. SMALLEY of Rice University have collaborated for the past seven years in research on carbon and semiconductor clusters in supersonic beams. Curl is a professor in, and chairman of, the department of chemistry. Smalley is the Gene and Norman Hackerman Professor of Chemistry and a professor of physics. For the past five years, he has also served as the chairman of the Rice Quantum Institute.

In addition to C_{60}, another molecule, C_{70}, appeared to be quite special in these early experiments. We soon found that the stability of C_{70} could be understood if the molecule had also taken the form of a geodesic dome. As Fuller had pointed out, all such domes can be considered networks of pentagons and hexagons. The 18th-century Swiss mathematician Leonhard Euler calculated that any such object must have precisely 12 pentagons in order to close into a spheroid, although the number of hexagons can vary widely. The soccerball structure of C_{60} has 20 hexagons, whereas the structure we proposed for C_{70} has 25, producing a shape reminiscent of a rugby ball.

In fact, we had found that all the even-numbered carbon clusters greater than about 32 atoms in size were remarkably stable (although less so than 60 or 70), and the evidence soon led us to postulate that all these molecules had taken the structure of geodesic domes. Again, in honor of Fuller, it seemed fitting to term this entirely new class of molecules the "fullerenes."

We later learned that such molecules had already been imagined. David E. H. Jones, writing under the pseudonym "Daedalus" in the *New Scientist* in 1966, had conceived of a "hollow molecule" made of curled-up graphitic sheets. Others had predicted the stability of C_{60} from calculations and tried—unsuccessfully—to synthesize it. We, however, were apparently the first to discover that the material could form spontaneously in a condensing carbon vapor.

Although our evidence was sound and our conclusions were supported by extensive further experiments and theoretical calculations, we could not collect more than a few tens of thousands of these special new molecules. This amount was plenty to detect and probe with the sophisticated techniques available in our laboratory, but there was not enough to see, touch or smell. Our evidence was indirect, much as it is for physicists who study antimatter. For now, the fullerenes existed only as fleeting signals detected in our exotic machines. But as chemists, we knew that the new material ought to be perfectly stable. Unlike antimatter, the geodesic forms of carbon should be quite safe to hold in one's bare hand. All we had to do was make more of them—billions and billions more.

Thus, for five years, we had been searching for a method of producing visible amounts of the stuff. We called our efforts "the search for the yellow vial" because quantum calculations for such a soccerball-shaped carbon molecule suggested it would absorb light strongly only in the far violet part of the spectrum. We were not alone. Our initial "soccerball"

HYPERFULLERENE STRUCTURE called a Russian egg is expected to form along with ordinary fullerenes in a laser-vaporized carbon plume. Shown here is the most symmetric form: a C_{60} at the core is encapsulated by fullerenes having 240, 540 and 960 atoms. This process could continue indefinitely to produce a macroscopic particle whose pentagons are in icosahedral alignment.

proposal, published in *Nature* in 1985, had made the quest one of the hottest in chemistry.

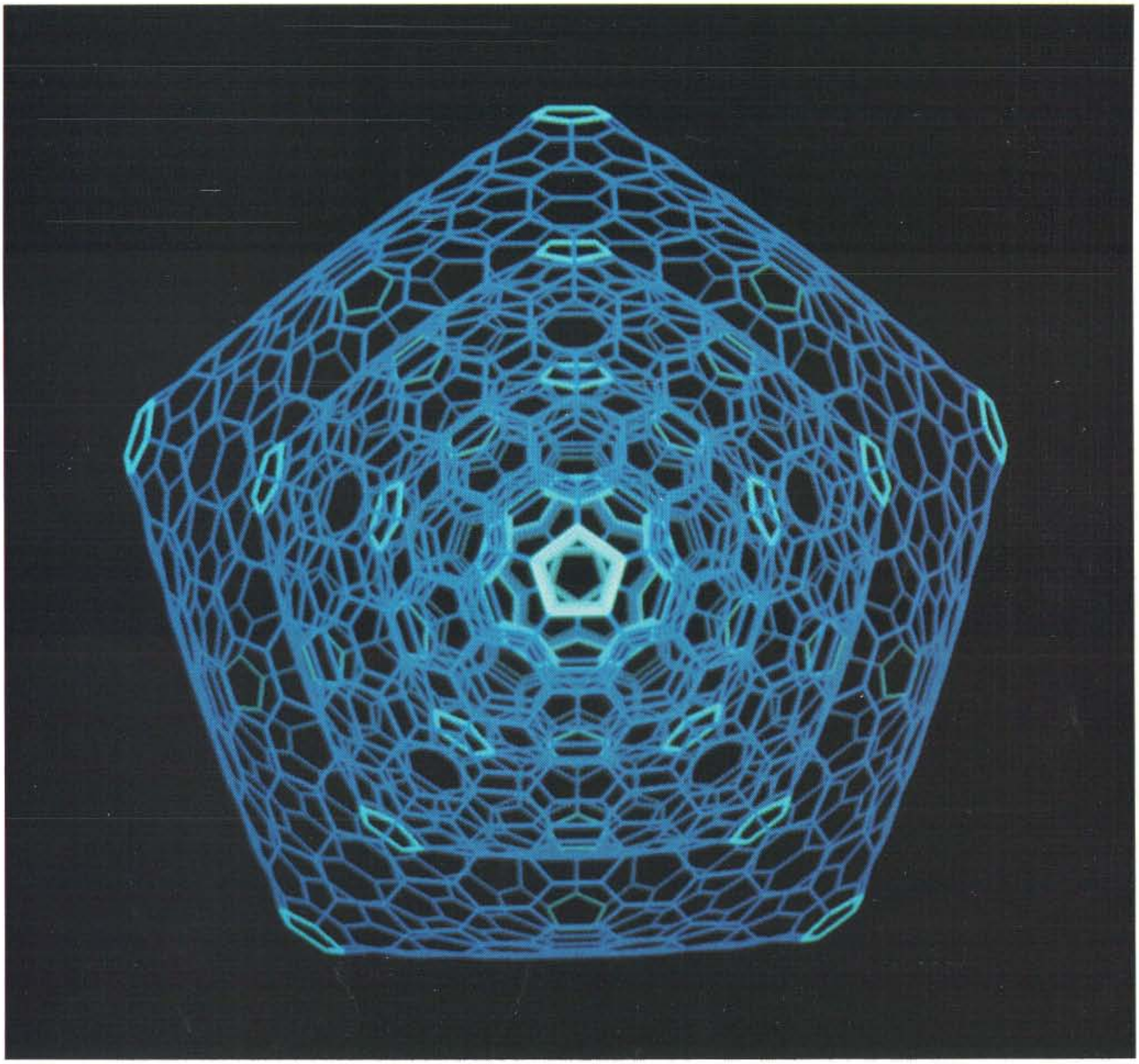
In our laboratory we collected the sooty carbon produced by the vaporization laser while using various chemical techniques to detect the presence of C_{60}. We slurried the soot in benzene, for example, and looked for a yellow color. But the solution in our test tubes stayed clear, with boring black soot sitting on the bottom. The community of cluster chemists ran many more sophisticated experiments but achieved no better result.

Many gave up hope of ever seeing the yellow vial. They reasoned that although the fullerenes may be stable, it was too hard to separate them from the other sooty material being produced in the vaporization experiments. Perhaps, the workers said, some dedicated chemist might one day extract a few micrograms with some special solvent, but no one seriously expected C_{60} to be available in bulk anytime soon.

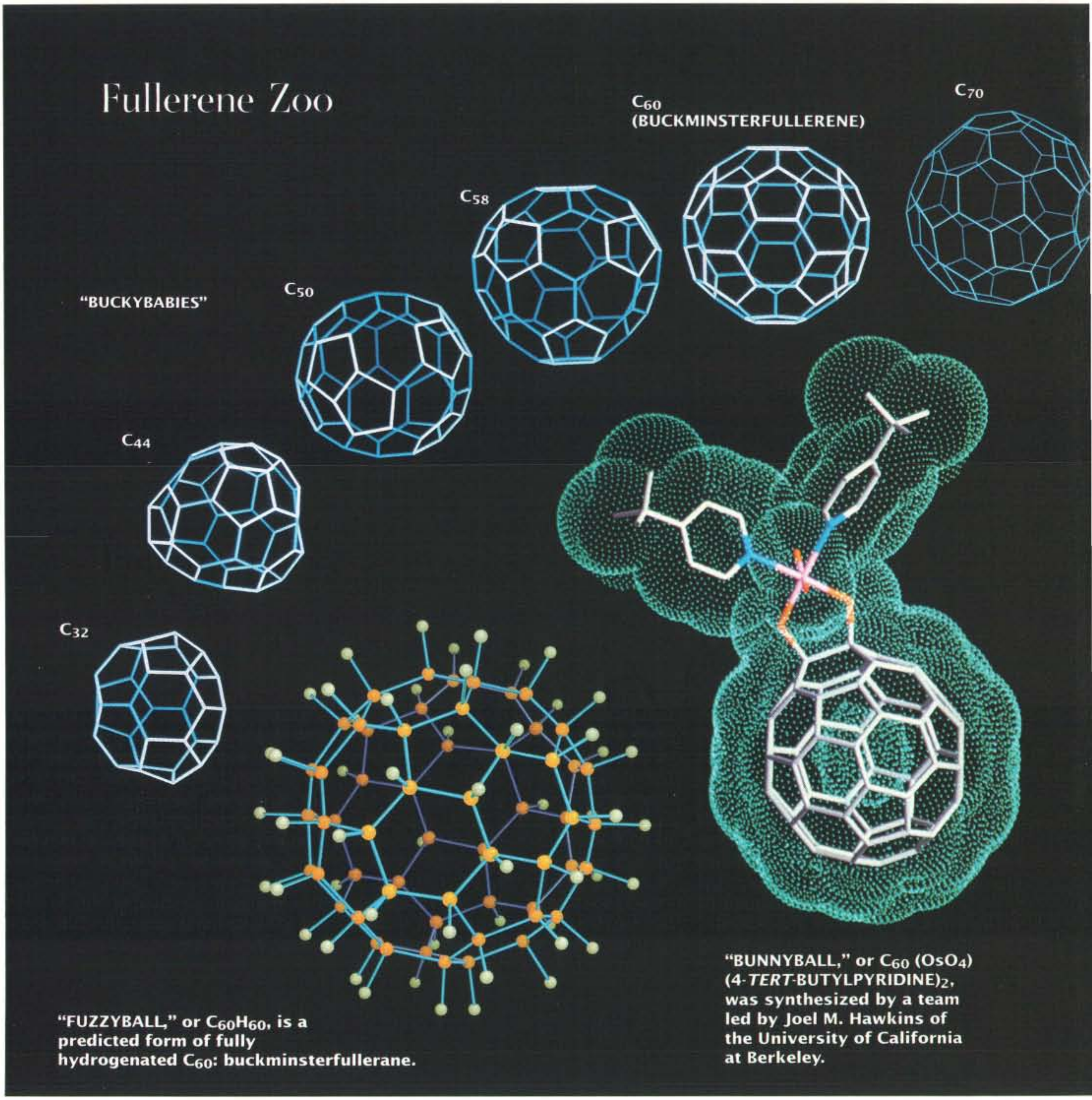
In the end, the breakthrough was made not by chemists but by physicists working in a totally different area. Huffman, Krätschmer and their students had been engaged for decades in a study of interstellar dust, which they assumed to consist mainly of particles of carbon (the most common particle-forming element). They therefore modeled the phenomenon in the laboratory by vaporizing carbon and condensing it in as many ways as possible. Optical tests figured in most of the studies. (Virtually all that is known of the interstellar dust stems from observations of how it absorbs and scatters starlight.)

In 1983 the physicists tried evaporating a graphite rod by resistive heating in an atmosphere of helium. They noticed that when the helium pressure was just right (about a seventh of an atmosphere), the dust strongly absorbed wavelengths in the far ultraviolet region, creating a peculiar, double-humped spectrum [*see bottom illustration on page 36*]. Most observers would have missed the two blips on the screen, but not Huffman and Krätschmer: they had studied spectra of carbon dust for years without encountering such an effect. They dubbed it their "camel" sample and wondered what it meant.

Nearly three years later, in the late fall of 1985, Huffman read in *Nature* of



Fullerene Zoo



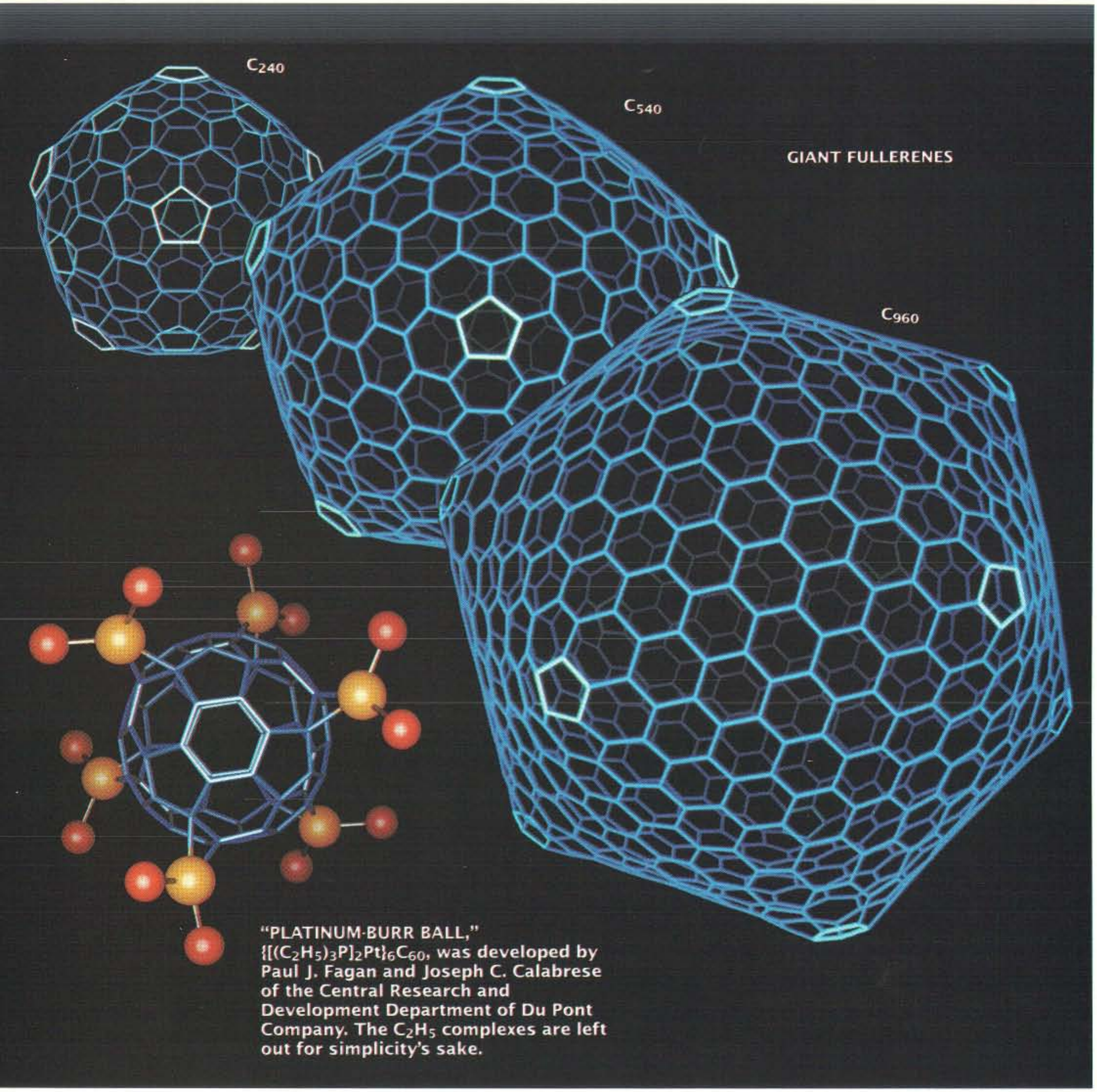
"FUZZYBALL," or $C_{60}H_{60}$, is a predicted form of fully hydrogenated C_{60}: buckminsterfullerane.

"BUNNYBALL," or $C_{60}(OsO_4)$(4-*TERT*-BUTYLPYRIDINE)$_2$, was synthesized by a team led by Joel M. Hawkins of the University of California at Berkeley.

our discovery of C_{60} and began to wonder if a hollow soccerball molecule might be the cause of the double hump. Yet this explanation seemed too good to be true, for it required that C_{60} account for a significant portion of the sample. Why would so much of the carbon end up in such perfectly symmetric cages? What did the helium do to make it possible? The seeming unlikeliness of this hypothesis, together with some difficulty in reproducing the experiment, led the researchers to put the project on the back burner.

By 1989, however, Huffman and Krätschmer had become convinced that the C_{60} hypothesis ought to be reexamined. They renewed their interest in the camel sample, readily reproducing the results of the 1983 experiments. This time their attention turned to measuring the sample's absorption of infrared light—the wavelengths that interact with the vibrational motion of molecules—in order to test the results against theoretical predictions that had by now been made for soccerball C_{60}. These predictions held that of the 174 vibrational modes of this putative molecule, only 46 would be distinct, and only four would appear in the infrared range. To their surprise, they found the camel sample did display four sharp infrared absorption lines, and they verified that the lines were present only in carbon dust produced in the special camel way. This finding provided striking evidence that C_{60} might be present in abundance.

Influenced by their background in physics, the workers initially chose to test their hypothesis by a rather in-



"PLATINUM-BURR BALL," $\{[(C_2H_5)_3P]_2Pt\}_6C_{60}$, **was developed by Paul J. Fagan and Joseph C. Calabrese of the Central Research and Development Department of Du Pont Company. The** C_2H_5 **complexes are left out for simplicity's sake.**

volved route. They prepared a sample from pure ^{13}C, a heavy isotope of carbon, and verified that the extra mass shifted the four infrared bands in the way expected for so large a molecule composed exclusively of carbon. Ultimately, however, they realized that the simplest assay followed a basic dictum of organic chemistry: like dissolves like. Should their sample dissolve in an aromatic solvent, such as benzene, this would support the predicted aromaticity of C_{60}. Because benzene molecules take the shape of a ring of carbon atoms, C_{60} would thus be seen as a kind of spherical benzene.

When the Krätschmer-Huffman group finally added benzene to their camel sample and saw the color red develop, they realized they were looking at the first concentrated solution of fullerenes ever seen. They evaporated the solvent and found that tiny crystals remained, which readily redissolved. These crystals could be sublimed under a vacuum near 400 degrees Celsius and condensed on a cold microscope slide to form smooth films of solid materials, which Krätschmer and Huffman christened "fullerite."

In thin layers these films were yellow (a fact that those of us at Rice University who searched for a "yellow vial" find highly gratifying). Although it took a while to obtain precise numbers, it is now known that carbon dust prepared in the camel way produces an extractable fullerene mixture made up of roughly 75 percent C_{60} (the soccerball), 23 percent C_{70} (the rugby ball) and a grab bag of larger fullerenes.

Here was a new form of pure, solid

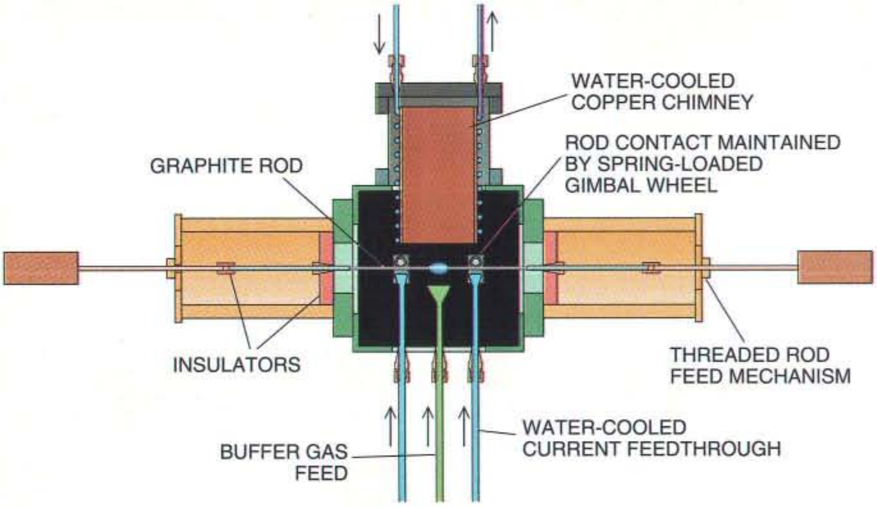
carbon. It is the only pure, finite form. The other two, diamond and graphite, are actually infinite network solids. In the real world, one usually deals with hunks of diamond cut out of larger bulk crystals. Under normal conditions, the surfaces of such a piece are instantly covered with hydrogen, which ties up the dangling surface bonds. Graphite is much the same. No piece of diamond, therefore, can ever be truly pure under normal conditions. The fullerenes, on the other hand, need no other atoms to satisfy their chemical bonding requirements on the surface. In this sense, the fullerenes are the first and only stable forms of pure, finite carbon.

Once the Krätschmer-Huffman results were announced at a conference in Konstanz, Germany, in early September 1990, the race was on. The study of C_{60} and the fullerenes had been the province of the few select groups that had something like our elaborate and expensive laser-vaporization cluster-beam apparatus. Now Krätschmer and Huffman had opened the field to anyone who could procure a thin rod of carbon, a cheap power supply, a bell-jar vacuum chamber and a few valves and gauges. Everybody could play.

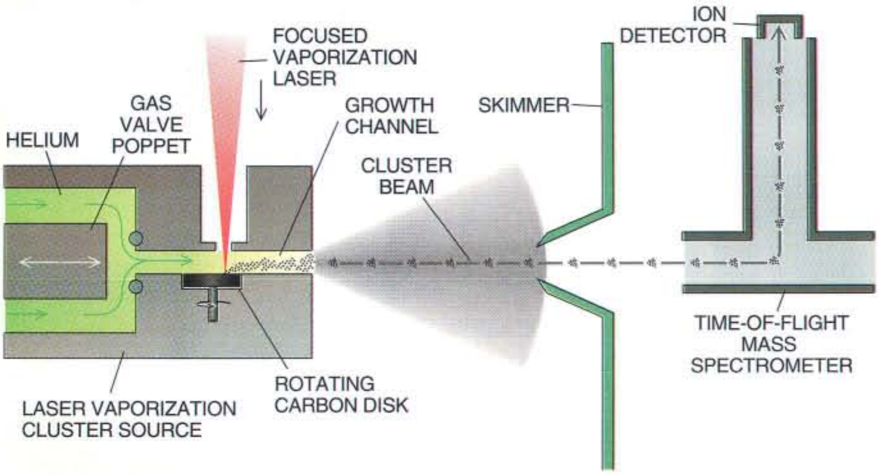
Within a few months, many groups were making their own fullerenes. Physicists, chemists and materials scientists thus began an interdisciplinary feeding frenzy that continues to intensify as this article is being written [*see box on page 40*]. The key results have been quickly reproduced in over a dozen laboratories, some of which have applied alternative procedures of verification as well. Because fullerenes are readily soluble and vaporizable molecules that remain stable in air, they are perfectly suited to a wide range of techniques.

One of the most powerful techniques—nuclear magnetic resonance (NMR)—has confirmed the single most critical aspect of the soccerball structure: that all 60 carbon atoms have exactly the same relation to the whole. Only the truncated icosahedral structure we proposed for C_{60} arranges the atoms so symmetrically as to distribute the strain of closure equally. Such even distribution makes for great strength and stability. Indeed, that is why we proposed the structure in the first place: it explains the extraordinary stability of the 60-atom species.

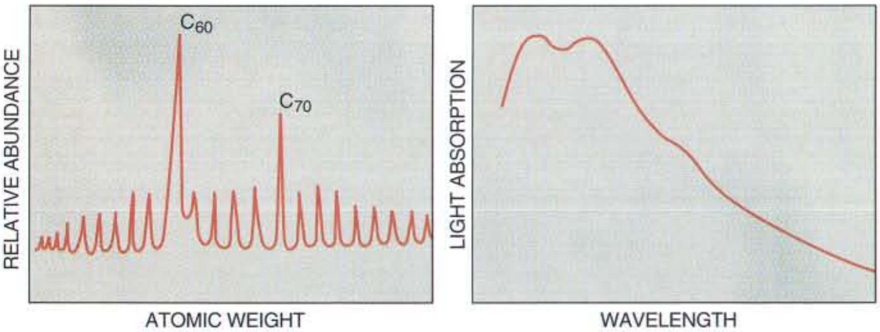
Because C_{60} is the most symmetric molecule possible in three-dimensional Euclidean space, it is literally the roundest of round molecules. Edgeless, chargeless and unbound, the molecule spins freely, as NMR experiments show,


WATER-COOLED COPPER CHIMNEY
ROD CONTACT MAINTAINED BY SPRING-LOADED GIMBAL WHEEL
GRAPHITE ROD
INSULATORS
THREADED ROD FEED MECHANISM
WATER-COOLED CURRENT FEEDTHROUGH
BUFFER GAS FEED

FULLERENE FACTORY makes macroscopic samples in a carbon arc. The arc—a refinement of an apparatus developed by Wolfgang Krätschmer and Donald Huffman—frees carbon atoms that coalesce into sheets. Inert helium holds the sheets near the arc long enough for them to close in on themselves, forming fullerenes.


FOCUSED VAPORIZATION LASER
ION DETECTOR
GAS VALVE POPPET
HELIUM
GROWTH CHANNEL
SKIMMER
CLUSTER BEAM
TIME-OF-FLIGHT MASS SPECTROMETER
ROTATING CARBON DISK
LASER VAPORIZATION CLUSTER SOURCE

CLUSTER GENERATOR designed by one of the authors (Smalley) produced the first evidence that fullerenes can form from carbon vapor. A pulsed laser vaporizes carbon; a gust of helium then sweeps the vapor into a supersonic beam whose expansion cools the atoms, condensing them.



CRUCIAL GRAPHS: in 1985 the cluster-beam generator showed many even-numbered carbon clusters, especially C_{60}, suggesting that these species are particularly stable. The humped ultraviolet absorption spectrum led Krätschmer and Huffman to dub it the "camel" sample; in 1990 it was shown to contain C_{60}.

more than 100 million times a second. The NMR experiments also dramatically verify that C_{70} has the shape of a tiny rugby ball: at room temperature, it spins rapidly about its long axis, stopping its frantic motion only below the temperature of liquid air.

High-resolution electron microscopy revealed these little carbon balls one at a time—as predicted, they spanned a bit more than one nanometer (a billionth of a meter). Scanning tunneling microscopy showed that when C_{60} molecules are deposited on a crystalline surface, they pack as regularly as billiard balls. X-ray diffraction studies demonstrated that—as one would expect—C_{60} crystallizes in a face-centered cubic lattice, with the balls a little more than 10 angstroms apart [*see illlustration on page 40*]. The crystals are as soft as graphite. When squeezed to less than 70 percent of their initial volume, calculations predict that they will become even harder than diamond. When the pressure is relieved, they are observed to spring back to their normal volume. Thrown against steel surfaces at speeds somewhat greater than 17,000 miles per hour (about the orbital speed of the U.S. space shuttle), they are incredibly resilient: they just bounce back.

We found that the most convenient way to generate fullerenes consists of setting up an arc between two graphite electrodes. We maintained a constant gap by screwing the electrodes toward each other as fast as their tips evaporated. The process worked best when the helium pressure was optimized and other gases, such as hydrogen and water vapor, were rigorously eliminated. Such measures produced yields of dissolvable fullerenes that typically ranged between 10 and 20 percent of the vaporized carbon. Yields as high as 45 percent have recently been reported.

The only irreducible cost appears to be that of the electricity needed to run the arc. But even the small bench-top generators we are now using in our laboratory provide electricity at a cost that amounts to only about five cents per gram of C_{60}. Recently it has been found that a sooting flame (such as that of a candle) can be used to produce substantial yields of C_{60}. In the long run, this may prove the cheapest way to make the material. When the first large-scale applications of fullerenes are found—perhaps in superconductors, batteries or microelectronics [*see box on page 40*]—the manufacturing cost of C_{60} will probably fall close to that of aluminum: a few dollars a pound. What had recently been described as the "most controversial molecule in the Cosmos" is well on its way to becoming a bulk commodity.

A host of questions arises out of this wonder. What exactly is the helium doing? How can such a perfectly symmetric molecule be formed with such high efficiency out of the chaos of a carbon arc? And, on a more personal level, where did we go wrong? Why did we, and all other chemists for that matter, fail in the search for the yellow vial? Our technique involved helium as well. What did the Krätschmer-Huffman team do that made such a big difference?

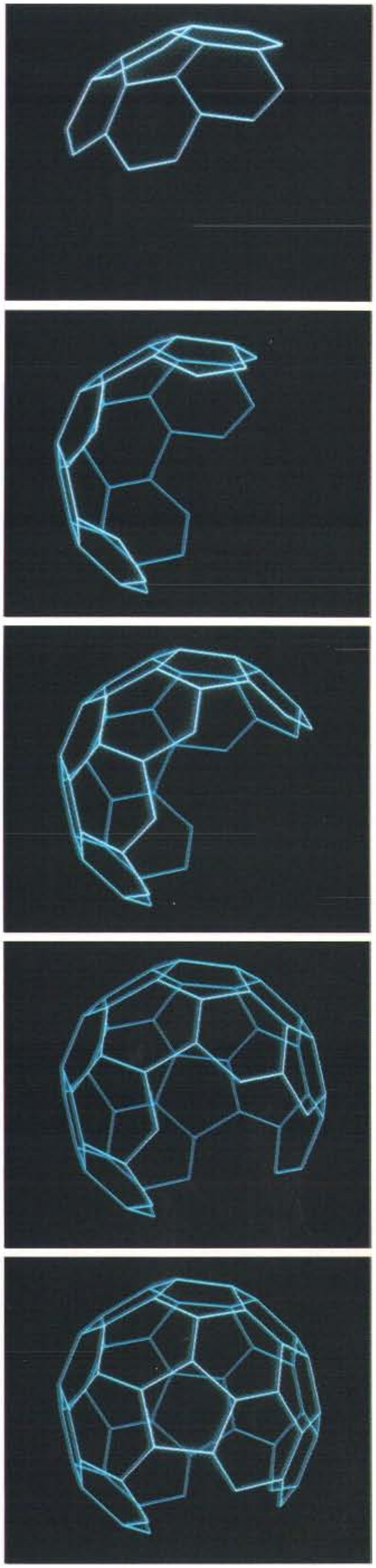
We now believe the answers to these questions lie in the way carbon vapor condenses at high temperatures. Linear carbon chains appear to link together to form graphitic sheets, and the sheets anneal as they grow in the hot vapor. Finally, stable, cagelike structures are favored by a key concept, which we call the pentagon rule.

Scientists had long known that when carbon is vaporized, most of its atoms initially coalesce into clusters ranging from two to 15 atoms or so. The very smallest carbon molecules are known to prefer essentially one-dimensional geometries. But clusters containing at least 10 atoms most commonly form a monocyclic ring—a kind of molecular Hula-Hoop that is especially favored at low temperatures. At very high temperatures, the rings break open to form units that comprise as many as 25 carbon atoms, taking the form of linear chains. Such chains might be imagined to look something like writhing snakes as they vibrate in the hot vapor.

It was these linear carbon chains that initially got us involved in carbon cluster studies and led to the discovery of C_{60}. Our British colleague, Harry Kroto, had theorized that the great abundance of such linear carbon chains in interstellar space may arise from chemical reactions in the outer atmospheres of carbon-rich red giant stars. In the early 1980s one of us (Smalley) had developed a supersonic cluster-beam device for the general study of small clusters composed of essentially any element in the periodic table [see "Microclusters," by Michael A. Duncan and Dennis H. Rouvray; SCIENTIFIC AMERICAN, December 1989].

We produced clusters by focusing an intense pulsed laser on a solid disk of the element to be studied. The local temperature could readily be brought above 10,000 degrees C—hotter than the surface of most stars and certainly hot enough to vaporize any known material. The resulting vapor was entrained in a powerful gust of helium, a chemi-

Growth of a Buckyball



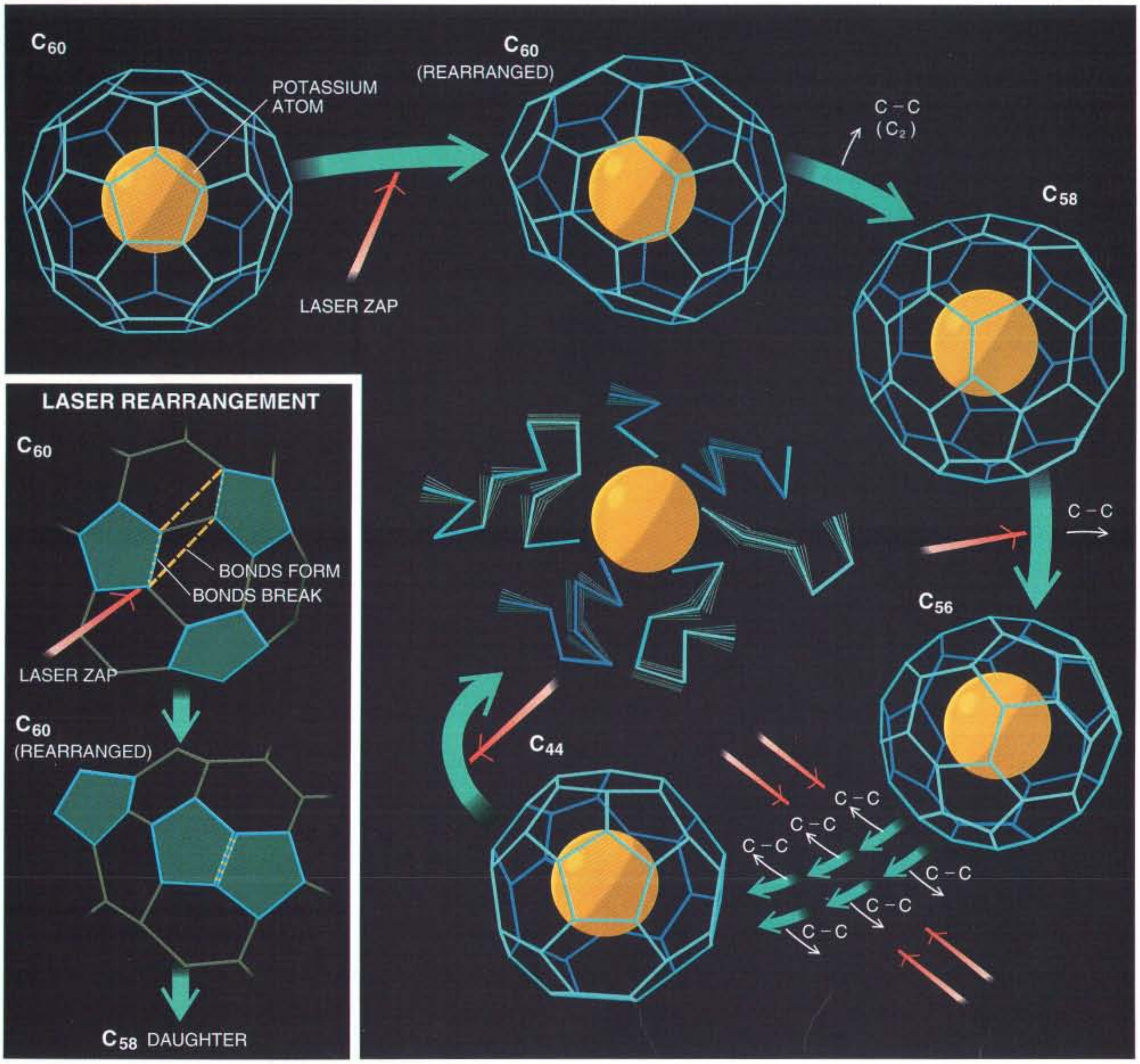
How to Shrink-Wrap an Atom

Laser vaporization of graphite (like the carbon-arc method) produces clusters whose sizes range from two atoms to thousands. We proved that all the even-numbered species between C_{32} and at least C_{600} are hollow, that is, they are fullerenes, by a method we call shrink-wrapping.

The technique involves suspending carbon clusters in a magnetic field and blasting them with a laser just powerful enough to knock pairs of carbon atoms out of the lattice. Each blast brings the fullerene down to the next smaller stage. The smooth progression of shrinking fullerenes ends abruptly at C_{32}, by which point the cage has become too brittle. The next blast bursts the molecule into linear-chain fragments.

We wondered what would happen if we folded a metal atom into the fullerene's core. Such an arrangement, we reasoned, ought to cause the laser blasts to shrink-wrap the metal atom in a carbon envelope. If the central atom is too large, shrinkage will terminate before C_{32} is reached. Indeed, it turns out that a potassium atom puts a stop to shrinking at C_{44}—the next laser blast blows the fullerene apart. Cesium, a slightly larger atom, bursts the bubble at C_{48}. These values are in perfect accord with what one would expect from the ionic radii of the two metals.

To date, laser vaporization has been shown to produce a wide variety of fullerene-caged metals—metallofullerenes. Atoms as heavy as lanthanum and uranium have been imprisoned. Theory suggests that metallofullerenes in bulk ("metallofullerite") would possess electrochemical properties that differ subtly, and perhaps usefully, from empty C_{60} cages. No macroscopic samples of the materials have been produced: the only fullerite now available encloses merely a vacuum. But the host of elements and even some molecules that will one day fill those holes promise a cornucopia that makes chemists' mouths water.



cally inert carrier gas, which cooled the vapor so that it could condense into small clusters. As the carrier gas expanded through a nozzle into a vacuum, it generated a supersonic beam of clusters whose sizes could be measured by a mass spectrometer.

In 1984 a group at Exxon using a copy of the cluster-beam apparatus developed at Rice had been the first to study carbon clusters in this fashion. Their results strongly suggested that the linear carbon chains Kroto wanted to study were in fact being produced in abundance. In addition, they reported a bizarre pattern among the larger clusters: the distribution was strikingly lacking in the species having an odd number of atoms.

The Exxon researchers recorded but did not notice that two particular even-numbered members, C_{60} and C_{70}, were somewhat more abundant than their neighbors [*see bottom illustration on page 36*]. The mysterious even-numbered distribution of clusters was separated from the small linear-chain distribution by what appeared to be something of a forbidden zone—a region of clusters between roughly 25 and 35 atoms in size in which few if any clusters could be detected.

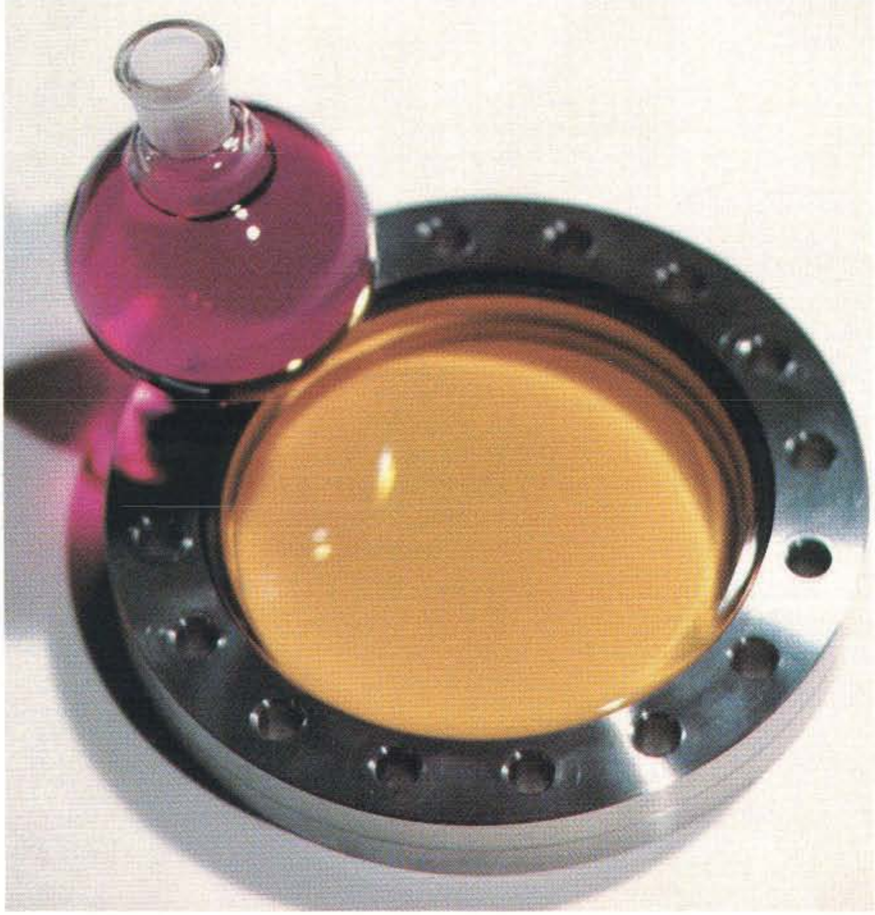
The even-numbered distribution was soon discovered to result from the fullerenes. In one of our many studies of Kroto's linear carbon chains, we reproduced the Exxon results but found something quite striking about the distribution of large, even-numbered clusters. Heath, Kroto and O'Brien noticed that the 60th cluster seemed five times more abundant than any other even-numbered cluster in the range between 50 and 70 atoms. This differential was dramatically greater than anything that had been seen before.

After much discussion, Heath and O'Brien spent the next weekend playing with the conditions in the laser-vaporization machine's supersonic nozzle. By Monday morning they had managed to find conditions in which C_{60} stood out in the cluster distribution like a flagpole. By the next morning we had had our Eureka! experience, and we were playing with every sort of soccerball we could get our hands on.

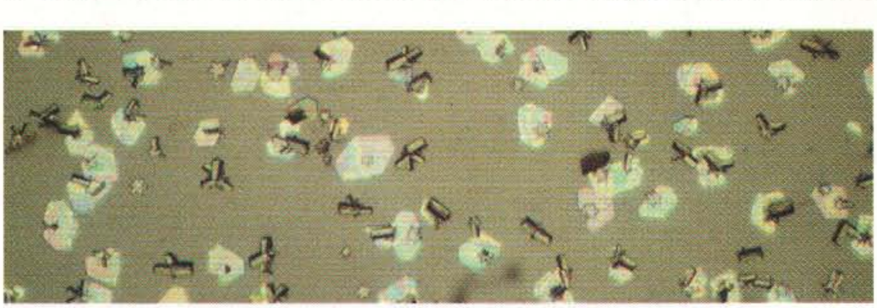
We found that we could explain the dominance of the even-numbered clusters by assuming they had all taken the structure of hollow, geodesic domes. They were all fullerenes. We could also argue that some fullerenes were more abundant than others because of the smoothness of the clusters' surface and the natural grouping of pentagons.

Pentagons provided an important clue. Although hundreds of examples are known in chemistry of five-membered rings attached to six-membered rings in stable aromatic compounds (for example, the nucleic acids adenine and guanine), only a few occur whose two five-membered rings share an edge. Interestingly, the smallest fullerene in which pentagons need not share an edge is C_{60}; the next is C_{70}. Although C_{72} and all larger fullerenes can easily adopt structures in which the five-membered rings are well separated, one finds that these pentagons in the larger fullerenes occupy strained positions. This vulnerability makes the carbon atoms at such sites particularly susceptible to chemical attack.

The big question, however, was not why fullerenes were stable but rather how they formed so readily in laser-vaporized graphite. Near the end of 1985, we suggested that the process began with linear chains. As the carbon vapor began to condense, the linear chains would grow long enough to flip back on themselves to form large monocyclic Hula-Hoops. As the growth continued, the chains would also fold into more effectively connected polycyclic network structures. Because graphite,



COLOR OF C_{60} depends on its form. This yellow film was sublimed onto a glass window that had been bolted to a vacuum oven. The benzene solution is magenta.



FULLERENE CRYSTALS were produced by evaporating a benzene solution of C_{60} containing a significant admixture of C_{70}.

the most stable known form of carbon, has its atoms bound in infinite hexagonal sheets, we suspected that the polycyclic network clusters resembled pieces of such sheets. We expected it to look like a fragment of chicken wire.

Like a cutout section of chicken wire, these graphitic sheets would have many dangling bonds, making them chemically reactive—much more so than the smaller linear chains, which have only two such bonds, one on each end. The sheets, therefore, would not be expected to be abundant in the cluster beams. Almost as soon as they form, they react with other small carbon molecules and grow too large to be seen. This, we believe, explains why there is a forbidden zone between the small linear-chain distribution and the first small fullerenes.

Chemists are conditioned to think of

Fullerene Electronics

Currently the most technologically interesting properties of bulk C_{60} are electronic: in various compound forms it functions as an insulator, a conductor, a semiconductor and a superconductor.

The material crystallizes when C_{60} molecules pack together like Ping-Pong balls in a face-centered cubic lattice. Calculations over the past few months have predicted that this new material is a direct band-gap semiconductor like gallium arsenide. All its units stand precisely at their posts in a crystalline structure. But unlike the elements of gallium arsenide, the buckyballs spin freely and at random. This disorder gives them a certain resemblance to amorphous silicon—a constituent of inexpensive solar cells. The peculiar disorder within order of bulk C_{60} has yet to be fully explored, but it is expected to produce a wholly new kind of semiconductor.

Early in 1991 researchers at AT&T Bell Laboratories discovered that they could mix, or dope, C_{60} with potassium to produce a new metallic phase—a "buckide" salt. It reaches its maximum electrical conductivity when there are three potassium atoms to each buckyball. If too much potassium is added, however, the material becomes insulating. Subsequent work has shown that K_3C_{60} is a stable metallic crystal consisting of a face-centered cubic structure of buckyballs, with potassium ions filling the cavities between the balls. Potassium buckide is the first completely three-dimensional molecular metal.

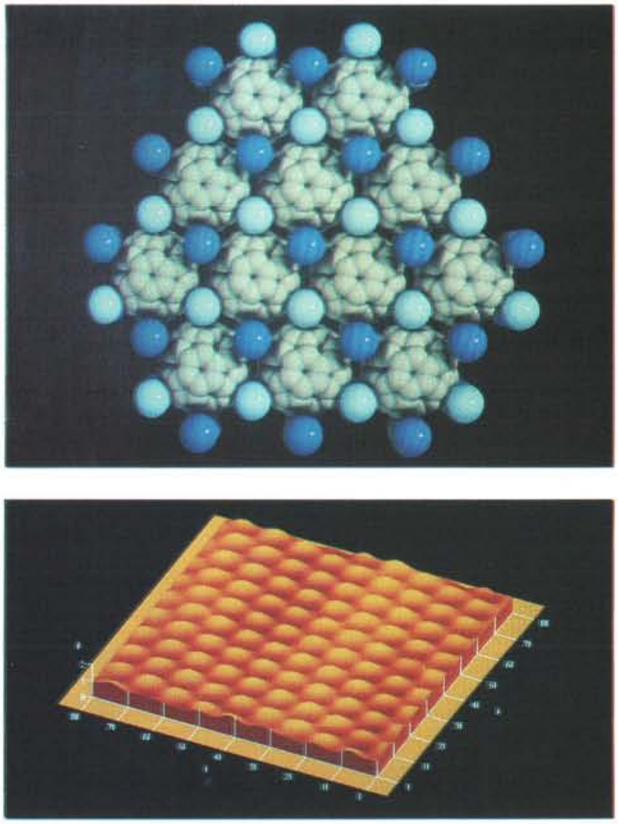
The Bell Labs team further discovered that this K_3C_{60} metal becomes a superconductor when cooled below 18 kelvins. When rubidium is substituted for the potassium, the critical temperature for superconductivity was found to be near 30 kelvins. (Recently workers at Allied-Signal, Inc., detected superconductivity at 43 kelvins for rubidium-thallium–doped material.) Careful work at the University of California at Los Angeles has shown that the superconducting phase is stable and readily annealed—imperfections can be smoothed away by heating and cooling.

The material can therefore be manufactured as a three-dimensional superconductor, making it a candidate for practical superconducting wires. Early estimates of magnetic and other characteristics indicate that these superconducting buckide salts are similar to the high-temperature superconducting ceramics made of yttrium, barium and copper oxide.

Recent work at the University of Minnesota has shown that highly ordered C_{60} films can readily be grown on crystalline substrates, such as gallium arsenide. This attribute makes the film a suitable material for microelectronic fabrication. Beautifully regular films of the K_3C_{60} superconductor can also be made [*see micrograph at right*], and the interface between the C_{60} crystalline film and the K_3C_{60} material has been found to be stable. It may thus lend itself to the production of intricately layered microelectronic devices.

In order for the semiconducting properties of fullerene materials to be thoroughly exploited, scientists need to learn how to dope them selectively to make *n*-type and *p*-type fullerene films, which donate electrons and holes, respectively. Such doping may involve putting a dopant atom inside the cage, either by growing the cage around the atom or by shooting atoms through the carbon walls by brute force. Small atoms, such as helium, have already been injected this way into the C_{60} cage, and it seems likely that hydrogen and lithium are insertable as well.

The versatility of bulk C_{60} seems to grow week by week. As we go to press, for example, there is a report suggesting that fullerene complexes exhibit ferromagnetic qualities in the absence of metals, an unparelleled phenomenon. Also, British workers from the universities of Leicester, Southampton and Sussex have just reported the generation of macroscopic quantities of fully fluorinated buckyballs ($C_{60}F_{60}$). The resulting "teflon balls" may be among the world's best lubricants. We do not know what the fullerenes' burgeoning traits will allow, but it would be surprising if the possibilities are not wonderful.



SUPERCONDUCTING FULLERIDE forms when buckyballs are doped with potassium in the ratio of K_3C_{60} (*diagram*), producing a crystal that can be grown on a gallium arsenide substrate (*scanning tunneling micrograph*).

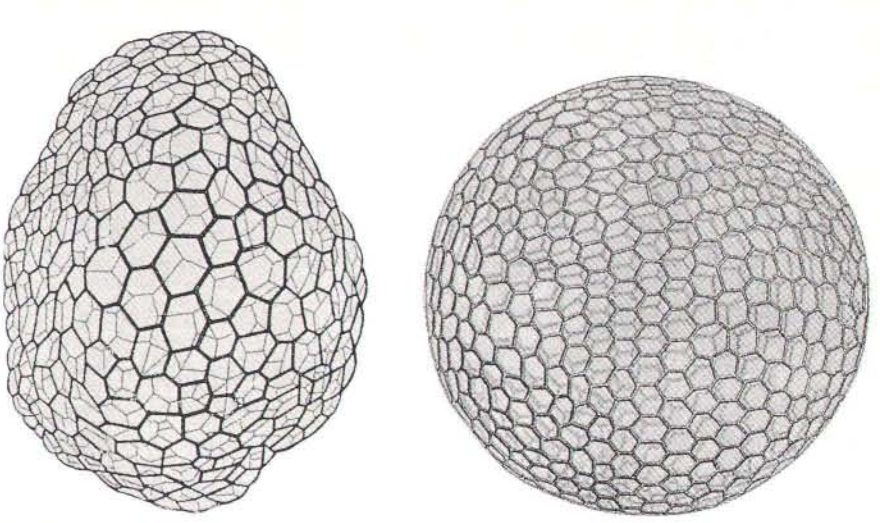
graphitic sheet structures as flat. After all, the sheets are certainly flat in a perfect crystal of graphite, and there is a huge class of very stable polycyclic aromatic hydrocarbons that are also flat (naphthalene and anthracene, for instance). But these free-floating graphitic sheets in the condensing carbon vapor have no atoms to tie up the dangling bonds on their edges. They therefore have little reason to remain flat. Indeed, the physical tendency to reach the lowest energy level available induces the sheets to eliminate their dangling bonds by curling up.

We discovered a strategy—the pentagon rule—according to which the sheets could accomplish this feat. The sheets rearrange their bonding so that pentagons are formed, causing the network to curve and permitting at least one good carbon-carbon bond to replace two dangling bonds. If some pentagons were good, more would be better. But we cautioned that it would be wise to avoid having two pentagons positioned so that they shared an edge, since this configuration is known to be rather unstable. If this process continues as the graphitic sheet grows, the network will naturally curl until the opposing edges meet to form the perfect soccerball structure. In this way, we argued in 1985, the formation of buckminsterfullerene from spontaneously condensing carbon vapor might not be so surprising after all.

Of course, there is no reason to expect that all growing graphitic sheets will close up—they merely have a theoretical propensity to do so. In reality, we expected clusters to grow too fast for imperfections to be corrected, so that the growing edge would typically overrun the opposite side, much like an overgrown toenail. Further growth would result in a spiraling nautilus-shaped structure that would prevent the growing edge from ever meeting its opposite, which would be hopelessly buried on the inside of the spiral.

This spiral shape seemed so interesting that we went on to suggest it may be formed in sooting flames and may in fact be the nucleus involved in the formation of soot. In this scenario, fullerenes like C_{60} and C_{70} are rather unlikely local stopping points in a curving, spiraling growth mechanism that ultimately results in soot.

Although this turned out to be a useful model, which within a few years led to the discovery that C_{60} and the other fullerenes are in fact abundant in all sooting flames, to some extent it misled us. Perfect closure need not always be that unlikely. Granted, the curving process is liable to be waylaid in a candle flame, where much hydrogen wanders around, tying up dangling bonds as it goes. These terminated dangling bonds would tend to frustrate the curving and closing mechanism.



LIVING FULLERENES: these radiolarians—protozoans having siliceous skeletons—appear in D'Arcy Thompson's 1917 classic, *On Growth and Form*.

But in a pure condensing carbon vapor one may be able to prolong the period in which the carbon nets remain open. If the temperature is kept high enough, the nets will effectively anneal, that is, they will adopt their most favored form by obeying the pentagon rule. Such conditions should thus produce a very high yield of C_{60}. This is what we believe Krätschmer and Huffman achieved. By using a simple, resistively heated graphite rod, they ensured that the concentration of small linear carbon radicals would be low and that the graphitic sheets would add these chains to their edges relatively slowly. The helium was critical, we believe, because it slowed migration of these chains away from the graphite rod. More chains lingered near the arc, which provided the heat they needed to continue to curve.

Not only was this line of reasoning available to us in 1985, it was a direct extension of the growth model we proposed at the time. Yet the yellow vial, so close to our grasp, eluded us because we did not think big. We were so intent on proving the existence of soccerball molecules that we asked no more of our model than that it rationalize tiny yields of C_{60}. Had we asked for more, had we considered the model's logical consequences, we would have—at least we should have—realized that we were heating and cooling the carbon too fast for it to anneal properly.

The solution would then have become obvious: the whole apparatus must be heated so that the laser-vaporized carbon plume expands further while it is still hot enough to anneal. Sure enough, when we finally did this in November 1990 by keeping the graphite target in an oven at 1,200 degrees C while passing helium over it slowly, a yellow-brown film of C_{60} and C_{70} rapidly sublimed on the surface of the oven. We found what we were looking for—five years late.

It appears, therefore, that a rather simple model explains the ready formation of this brand-new class of carbon molecules. Amazingly, C_{60} appears to result inevitably when carbon condenses slowly enough and at a high enough temperature. This discovery has come a bit later than it should have. But no matter: now we have it. And now the real fun can begin!

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End of the Proterozoic Eon

Some 800 million years ago the earth entered a period of major tectonic and environmental change. An increase in oxygen levels probably occurred at this time, which in turn may have opened the door to large animals

by Andrew H. Knoll

Living organisms have inhabited the surface of our planet for nearly four billion years. Yet the plants and animals that define our everyday existence have far more recent origins. The ancestors of modern trees and terrestrial animals first colonized land only about 450 million years ago. In the oceans, animals have a longer record, but macroscopic invertebrates did not appear even there until about 580 million years ago—roughly 85 percent of the way through life's history. The earliest animals, which are collectively referred to as the Ediacaran fauna (after the Ediacara Hills in southern Australia), have intrigued paleontologists since their discovery more than 50 years ago [see "The Emergence of Animals," by Mark A. S. McMenamin; SCIENTIFIC AMERICAN, April 1987].

The surprisingly young age of the fossils presents a most interesting puzzle. If life is so ancient, why did animals appear so late in the evolutionary day? Why—once the basic blueprint of life was drawn—did animals not emerge for more than three billion years? Alternatively, is the fossil record misleading? Is it possible that animals are far older than the record suggests?

ANDREW H. KNOLL is professor of organismic and evolutionary biology, and also earth and planetary sciences, at Harvard University. His interest in the evolution of life, which was sparked during his undergraduate days at Lehigh University, was fanned to a flame under the tutelage of the late Elso Barghoorn, who was Knoll's adviser and predecessor at Harvard. An avid field geologist, he has traversed the globe, spending nights in such remote areas as the high Arctic, the Australian Outback and the Namib desert of Namibia. Knoll is recipient of the Charles Schuchert Award of the Paleontological Society of America and the Charles Doolittle Walcott Medal of the National Academy of Sciences. In 1991 he was elected to the National Academy of Sciences.

To answer these questions, my colleagues and I have spent much of the past 15 years traveling to remote corners of the world searching for clues to the early evolution of life. By sifting through ancient sediments, we have sought to understand the nature of life just before the Ediacaran animals appear in the fossil record and to identify environmental factors that may explain the timing of their appearance.

Our time has been well spent. We now know that the Ediacaran radiation was indeed abrupt and that the geologic floor to the animal fossil record is both real and sharp. More important, we have reason to believe that the emergence of animals was closely linked to unprecedented changes in the earth's physical environment, including a significant increase in atmospheric oxygen that may have made the evolution of large animals possible.

Before I present the evidence on which we have based such conclusions, our findings must be placed within the framework of geologic time. Earth history is conventionally divided into three eons. The oldest is the Archean, which encompasses earth history from its origin until 2.5 billion years ago; the most recent eon is the Phanerozoic, which began with the expansion of skeleton-forming organisms 540 million years ago and continues to the present day. Separating them is the Proterozoic eon, which lasted for 2.1 billion years. It is near the end of the Proterozoic when the events described in this article took place.

Many paleontologists have been enticed by the mystery of early animal evolution. But while many of my colleagues have concentrated on identifying and classifying the first animal fossils, my goal has been to place the fossils in the context of a wider pattern of late Proterozoic biological and environmental change. Doing so, however, required that I find exceptionally well preserved sedimentary deposits, ones laid down just before the Ediacaran radiation.

Fortunately, a few such records exist. One of the best can be found in the glaciated mountains of Spitsbergen, a small island halfway between the northern tip of Norway and the North Pole. Here glaciers have exposed about 7,000 meters (22,000 feet) of gently folded but essentially unmetamorphosed sedimentary rocks that reflect shallow ocean conditions from about 600 to 850 million years ago. Throughout the past decade, Keene Swett of the University of Iowa and I have analyzed these rocks for signs of biological and environmental change.

As it turns out, Spitsbergen rocks provide an unmatched portrait of the earth and its biota as they existed just before the Ediacaran radiation. Indeed, the richness of the Spitsbergen fossil record has enabled us to make a number of significant discoveries. To begin with, we found the Spitsbergen fossils not only represent a variety of habitats but belong to morphologically and taxonomically diverse taxa. In addition, both prokaryotic and eukaryotic cell types are present in the sediments. Prokaryotes are generally simple organisms whose cells lack nuclei and other organelles; they are represented by bacteria, including the cyanobacteria, or blue-green "algae." According to Julian W. Green, a former student in my laboratory, who is now at the University of South Carolina at Spartanburg, many of the prokaryotes from Spitsbergen and related areas exhibit characteristics of morphology, development and behavior (as inferred from their orientations in the sediments) that

SEDIMENTARY OUTCROPS in Spitsbergen (as well as in eastern Greenland) have provided much information about the earth during the late Proterozoic eon. The rocks reveal, among other things, that macroscopic animals appeared on the earth rather abruptly.

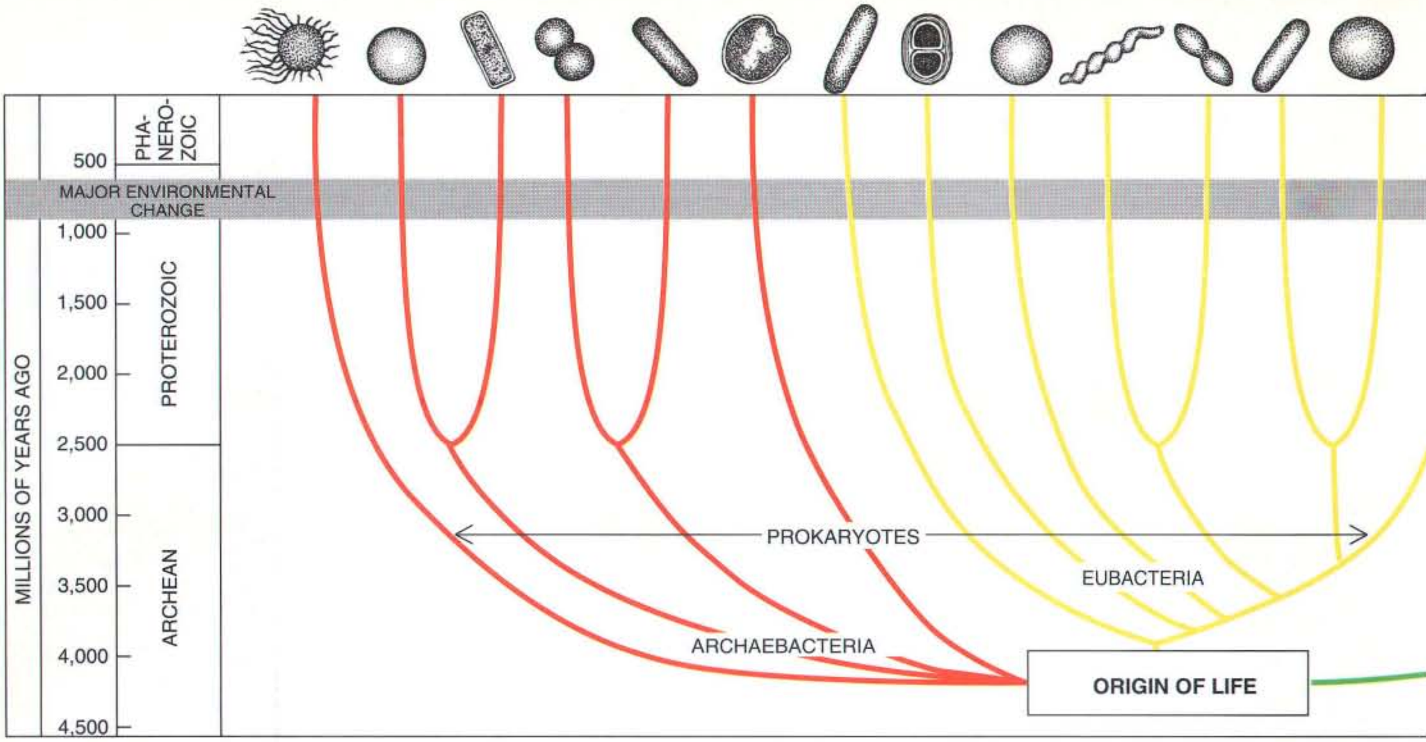
render them virtually indistinguishable from cyanobacteria and other bacteria that live in comparable habitats today.

Eukaryotes, which include single-celled protozoa and algae as well as multicellular plants, animals and fungi, differ from prokaryotes in having nuclei bounded by a membrane; most also have energy-yielding processes localized in organelles such as mitochondria and chloroplasts. Some Spitsbergen eukaryotes resemble modern prasinophyte (green) algae, whereas others bear closer resemblance to the so-called chromophyte algae such as the dinoflagellates that are ubiquitous in modern oceans.

Most exhibit an evolutionary pattern quite unlike that of the prokaryotes in the same rocks. By comparing fossils from sediments ranging in age from 600 to 850 million years old, we found that single-celled eukaryotes underwent marked diversification during the late Proterozoic. In contrast to coeval prokaryotes, which display apparent stasis and are modern in aspect, the eukaryotes show patterns of diversification, evolutionary turnover and extinction more like those of Phanerozoic plants, animals and microplankton.

We also discovered that not all Spitsbergen fossils are unicellular. Nicholas Butterfield, a graduate student in my laboratory, has found beautifully preserved multicellular algae (seaweeds) in strata that are approximately 800 million years old. Several major groups of algae are represented, including species that once formed extensive carpets on the quiet, subtidal seafloor.

Despite the presence of multicellular algae and diverse single-celled eukaryotes, there are no indications of animal life in the Spitsbergen sediments. Tracks, trails or burrows normally associated with animal activity simply have not been found in these rocks or in other beds of comparable age. This



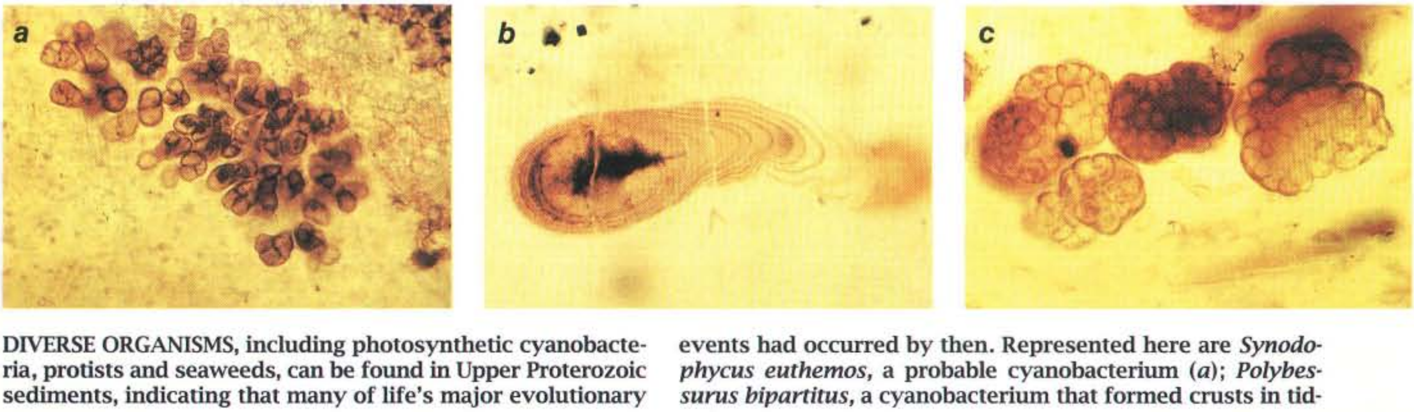
finding, combined with the fact that many of the sediments are finely laminated, offers compelling evidence that animals large enough to disrupt fine-scale bedding did not exist at that time.

Logically, there must have been a period of animal prehistory preceding the Ediacaran radiation; molecular estimates suggest that animals originated from 800 to 1,000 million years ago. Such dates can be reconciled with the geologic record if one accepts the prevailing view that the earliest animals were tiny, soft-bodied forms that eluded fossilization. Thus, the appearance of the Ediacaran fauna signals not so much the attainment of multicellularity (after all, seaweeds and microscopic animals possess complex modes of development) but the attainment of macroscopic size in animals.

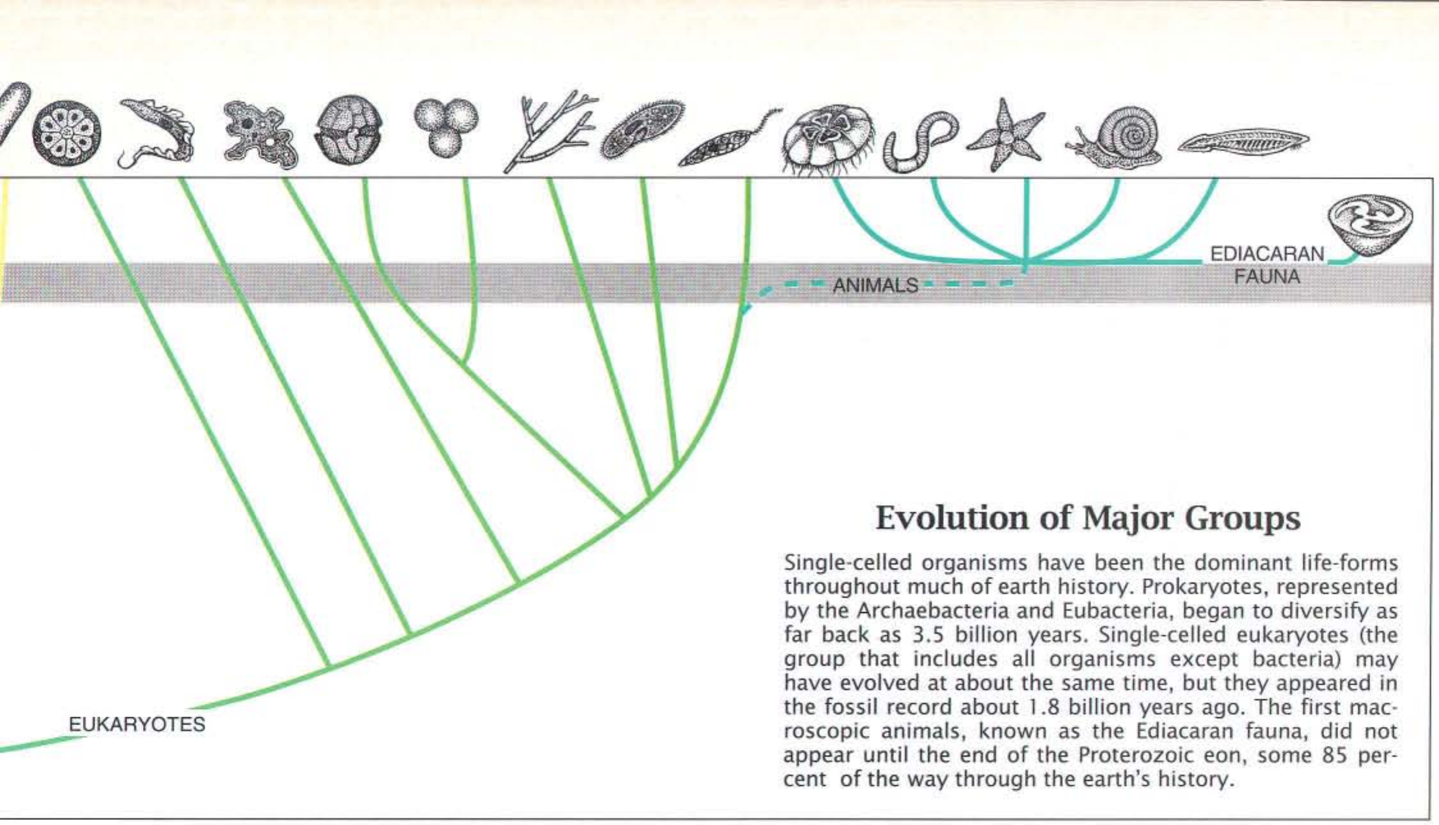
What factors might have deterred the emergence of large animals until so late in the evolutionary day? The Proterozoic radiation of single-celled algae and protozoa might suggest that evolution of the eukaryotic cell was a limiting factor, but such a notion is put to rest by the discovery of eukaryotic fossils in sediments much older than those in Spitsbergen. Simple spheroidal vesicles that are reasonably interpreted as resting cysts produced by algae have been found in rocks that are roughly twice as old as the Spitsbergen strata. In addition, steranes, which are the geologic form of sterols (molecules thought to be synthesized exclusively by nucleated cells), have been identified in petroleum deposits at least 1.7 billion years old by Roger E. Summons and his colleagues at the Australian Bureau of Mineral Resources, Geology and Geophysics. Clearly, eukaryotic cells arose more than a billion years before the Ediacaran radiation and may have arisen much earlier. Carl Woese of the University of Illinois at Urbana-Champaign and others have inferred from molecular comparisons of living species that eukaryotes arose fully as early as prokaryotes.

In addition, Spitsbergen and older rocks show that the evolution of multicellularity did not directly trigger the Ediacaran radiation. Multicellular eukaryotes (seaweeds) have been found in 1.4-billion-year-old strata by Du Rulin of the Hebei Institute of Geology.

All evidence, therefore, points in one direction. Namely, that long before the Ediacaran radiation there existed complex communities of bacteria and protists, including both autotrophic forms (those that produce



DIVERSE ORGANISMS, including photosynthetic cyanobacteria, protists and seaweeds, can be found in Upper Proterozoic sediments, indicating that many of life's major evolutionary events had occurred by then. Represented here are *Synodophycus euthemos*, a probable cyanobacterium (*a*); *Polybessurus bipartitus*, a cyanobacterium that formed crusts in tid-



Evolution of Major Groups

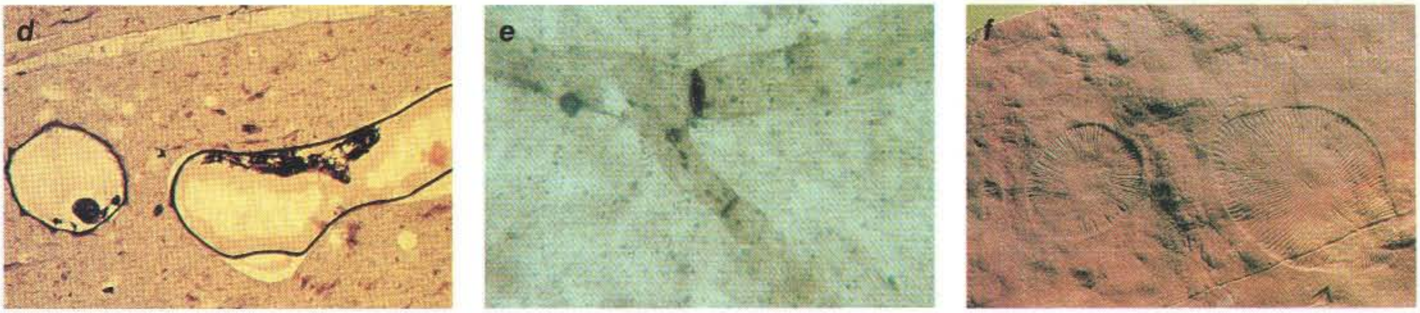
Single-celled organisms have been the dominant life-forms throughout much of earth history. Prokaryotes, represented by the Archaebacteria and Eubacteria, began to diversify as far back as 3.5 billion years. Single-celled eukaryotes (the group that includes all organisms except bacteria) may have evolved at about the same time, but they appeared in the fossil record about 1.8 billion years ago. The first macroscopic animals, known as the Ediacaran fauna, did not appear until the end of the Proterozoic eon, some 85 percent of the way through the earth's history.

organic matter from inorganic molecules) and heterotrophic ones (those that feed on organic matter produced by other organisms), seaweeds and perhaps even tiny ancestral metazoans. Food webs in these ancient communities were undoubtedly complex, and with the exception of the biogenic silica cycle (which is controlled principally by skeleton-forming sponges, diatoms and radiolarians that did not appear until later), all major biogeochemical cycles were well established.

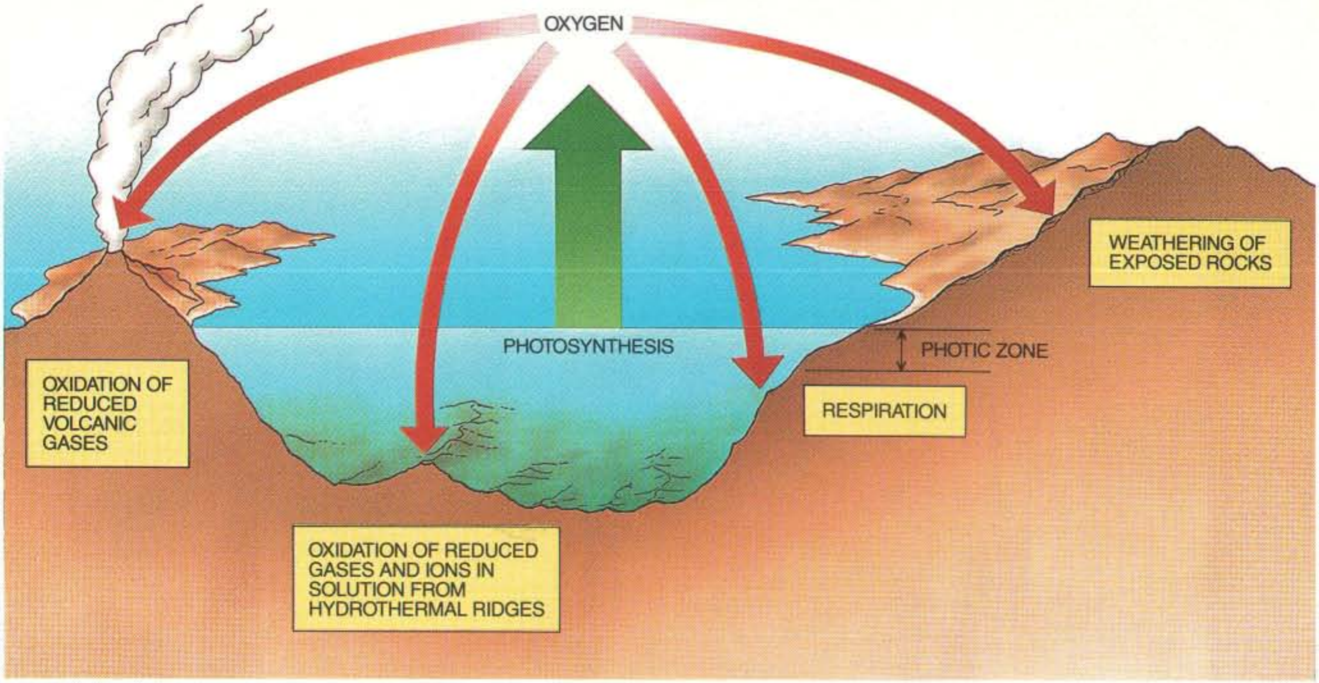
We are certain, therefore, that the Ediacaran animals did not radiate into a world devoid of diversity but rather into one that was ecologically complex and taxonomically diverse. This provides the evolutionary framework within which early metazoan evolution must be understood. Equally important, however, is the environmental context.

What physical events might have facilitated the evolution of macroscopic animals? Specifically, what kind of environmental barrier might have separated a world inhabited by unicellular organisms and seaweeds from one harboring large animals? A credible answer to this question was offered more than 30 years ago by J. Ralph Nursall of the University of Alberta, who proposed that throughout most of earth history (until the time of the Ediacaran radiation), levels of atmospheric oxygen were too low to permit metabolic activity by macroscopic invertebrates. Since then, the idea has been championed by many paleontologists and biologists, most notably by Preston Cloud of the University of California at Santa Barbara, who has long argued that important clues to biological evolution reside in the geochemical record of sediments.

The most widely cited "oxygen control" hypothesis was proposed more than 25 years ago by Lloyd V. Berkner and Lauriston C. Marshall of the Graduate Research Center of the Southwest in Dallas. They suggested that oxygen did not rise above 1 percent of present-day atmospheric levels until the end of the Proterozoic eon. Only then would aerobic metabolism have been possible and would sufficient ozone have accumulated in the atmosphere to absorb the sun's lethal ultraviolet radiation. Most researchers still consider 1 percent of present-day levels to be a critical threshold for biological activity, but it is now clear that this threshold was crossed at least 1.3 billion years before the Ediacaran event, ruling out a direct relation to the appearance of large animals. Nevertheless, atmospheric oxygen cannot be disregard-



al environments (*b*); *Hyella dichotoma*, a cyanobacterium that bored through carbonate sediments (*c*); *Trachyhystrichosphaera vidalii*, a large, unicellular alga (*d*); and a multicellular green alga or seaweed (as yet unnamed) (*e*). Macroscopic animals, such as *Dickinsonia costata* (*f*), did not appear until near the end of the Proterozoic, 580 million years ago.


OXYGEN
PHOTOSYNTHESIS
PHOTIC ZONE
WEATHERING OF EXPOSED ROCKS
OXIDATION OF REDUCED VOLCANIC GASES
RESPIRATION
OXIDATION OF REDUCED GASES AND IONS IN SOLUTION FROM HYDROTHERMAL RIDGES

MAJOR SOURCES AND SINKS exist for atmospheric oxygen. Cyanobacteria and algae, which produce oxygen as a byproduct of photosynthesis, were the important sources of oxygen during the late Proterozoic. The respiratory activity of these and nonphotosynthetic organisms in turn created the largest sink. Other sinks include the weathering of exposed rocks and the reduction of volcanic and hydrothermal-vent gases and ions in solution.

ed as a factor in metazoan evolution.

To begin with, although 1 percent of present-day atmospheric levels represents a critical threshold for oxygen-dependent cells and minute, architecturally simple animals, macroscopic animals demand much higher oxygen concentrations. Physiological functions that require significantly higher oxygen levels include collagen synthesis, exercise metabolism and oxygenation of the body's tissues.

Taking such functions into account, Bruce Runnegar of the University of California at Los Angeles has estimated that the relatively simple invertebrates found in Ediacaran assemblages would have needed oxygen at concentrations equal to or greater than 6 to 10 percent of present-day atmospheric levels. His estimate assumes that Ediacaran animals had well-developed circulatory systems capable of transporting oxygen efficiently to their tissues. But it is likely that the first macroscopic animals lacked such sophisticated circulation and instead oxygenated their cells by means of simple diffusion. In this case, substantially higher oxygen levels (perhaps comparable to those of today) would have been necessary to sustain macroscopic animals.

Recognition that the first large animals had high oxygen requirements allows us to reformulate the oxygen control hypothesis, substituting a higher threshold value than the one envisioned by Berkner and Marshall. Nevertheless, the hypothesis is based entirely on the physiological needs of living organisms. Although such data are consistent with a late Proterozoic increase in atmospheric oxygen, they do not prove that such an increase actually occurred.

Desiring such proof, my colleagues and I set out to examine the late Proterozoic sedimentary record for concrete evidence of changing oxygen levels. Although the oxygen content of Proterozoic air cannot be measured directly, our data do show that the earth underwent a number of profound physical changes near the end of the Proterozoic, quite likely including a significant rise in atmospheric oxygen.

Before our findings can be interpreted, the source of free oxygen must be determined. Most scientists agree that the amount produced by nonbiological processes is negligible; virtually all free oxygen comes from photosynthesis, the process by which green plants, algae and cyanobacteria use the sun's energy to convert carbon dioxide and water to sugars (which the cells then sequester) and oxygen (which is released as a byproduct). Most of the time, atmospheric oxygen appears to be in a steady state. That is, the amount of oxygen generated by photosynthesis is balanced by the amount of oxygen consumed by biological and geologic activities. Such activities include respiration (the process by which organisms use oxygen to derive energy from organic molecules), weathering (the oxidation of reduced sulfur, iron and other materials in exposed rocks) and oxidation of reduced gases given off by organisms and volcanoes. Only when the amount of oxygen released during photosynthesis exceeds the amount consumed by oxidation will oxygen levels increase.

It seems reasonable that a buildup of atmospheric oxygen will ensue if more and more photosynthetic organic matter is produced. But this is not necessarily so, because the oxygen produced by photosynthesis is usually consumed by higher rates of respiration or weathering. Oxygen levels are most likely to rise not when more photosynthetic matter is produced but when more is buried in sediments. Recall that during photosynthesis organic matter is synthesized and oxygen released. Because removal of organic matter by burial decreases the amount of organic material available for respiration, the net result is a buildup of oxygen. (Of course, oxygen will accumulate in the atmosphere only if it is not consumed by weathering and other oxidation reactions.)

To our good fortune, the relation between oxygen production and organic carbon burial provided a way to assess environmental change during the late Proterozoic. If oxygen levels increased during that period, we could expect to find the increase reflected in higher rates of organic carbon burial. Although such rates are difficult to measure directly, the isotopic composition of carbon in ancient carbonates and organic matter provides a useful estimate.

Let me explain why. The element carbon has two stable isotopes: ^{12}C, which contains six protons and six neutrons and makes up about 99 percent of all carbon atoms, and ^{13}C, which has an extra neutron and is thus heavier. (A very small fraction of carbon atoms has eight neutrons, forming the radioactive isotope ^{14}C; because this isotope decays to nitrogen with a half-life of only a few thousand years, it does not figure in discussions of Proterozoic carbon.)

Carbon occurs principally in carbonate minerals such as calcite and aragonite, as well as in dolomite (which also contains magnesium) and organic matter. Once formed, the ratio of ^{13}C to ^{12}C in these materials changes only slightly over time. The ratio depends mainly on isotopic fractionation associated with the preferential uptake of ^{12}C (the lighter isotope) during photosynthesis, but to some degree it also depends on the relative fluxes of carbonate and organic matter in and out of sediments [*see illustration below*].

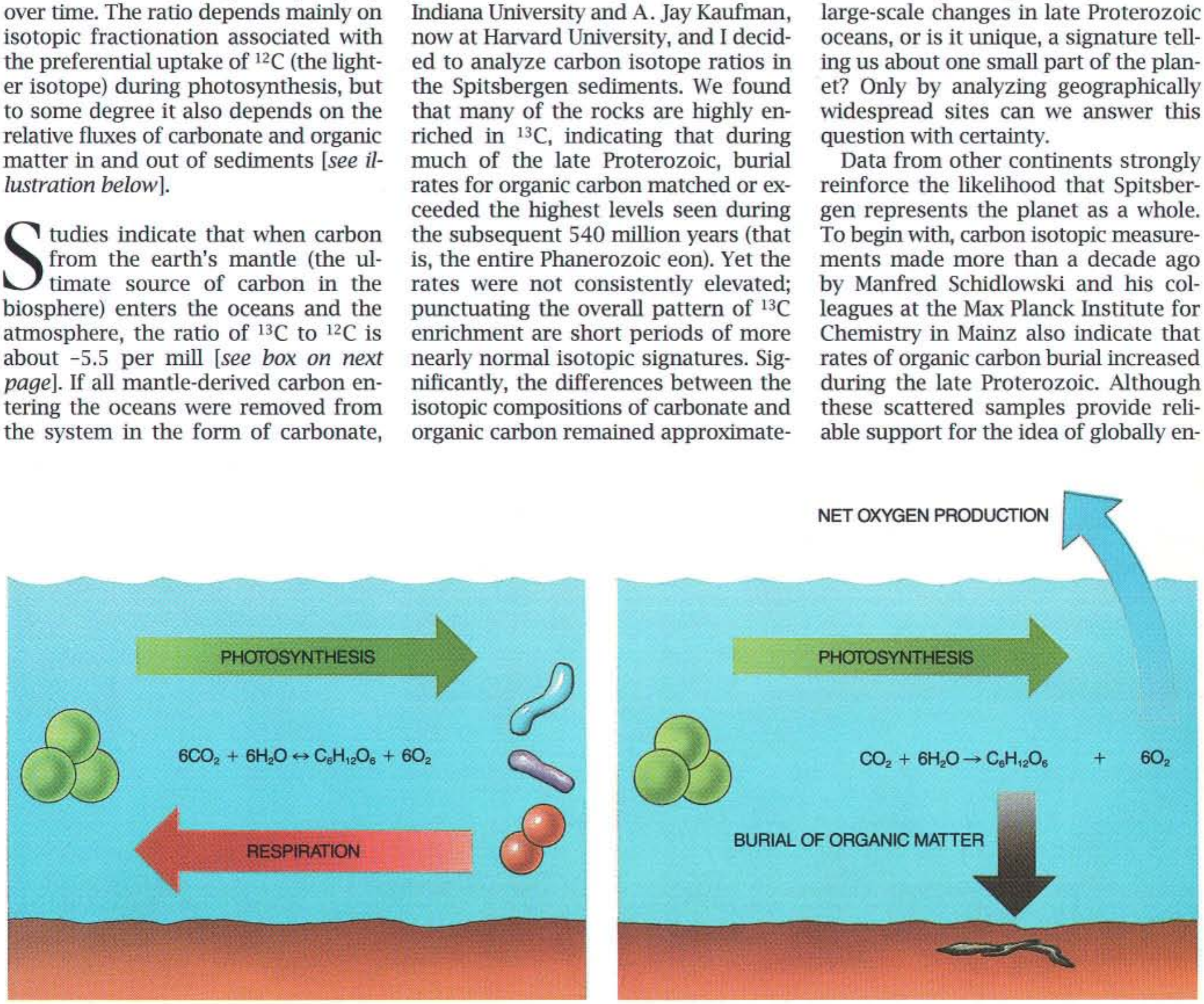
Studies indicate that when carbon from the earth's mantle (the ultimate source of carbon in the biosphere) enters the oceans and the atmosphere, the ratio of ^{13}C to ^{12}C is about -5.5 per mill [*see box on next page*]. If all mantle-derived carbon entering the oceans were removed from the system in the form of carbonate, the ratio of carbon isotopes in the carbonate would be the same as in the source, that is, -5.5 per mill. The same relation would hold true if all carbon in circulation were somehow removed and stored as organic matter. In other words, the amount of ^{13}C and ^{12}C entering and leaving the oceans and atmosphere remains essentially constant.

As a consequence, any change in the relative proportion of carbonate and organic matter removed by sedimentary burial will be matched by a shift in their isotopic compositions. Changes in the proportions of carbonate and organic carbon burial are thought to stem mostly from variations in organic deposition. Thus, by measuring the ratio of ^{13}C to ^{12}C in a sedimentary profile, which reflects rates of organic carbon burial at the time of deposition, changes over time can be estimated.

With this in mind, John M. Hayes of Indiana University and A. Jay Kaufman, now at Harvard University, and I decided to analyze carbon isotope ratios in the Spitsbergen sediments. We found that many of the rocks are highly enriched in ^{13}C, indicating that during much of the late Proterozoic, burial rates for organic carbon matched or exceeded the highest levels seen during the subsequent 540 million years (that is, the entire Phanerozoic eon). Yet the rates were not consistently elevated; punctuating the overall pattern of ^{13}C enrichment are short periods of more nearly normal isotopic signatures. Significantly, the differences between the isotopic compositions of carbonate and organic carbon remained approximately constant throughout the Spitsbergen record. This finding and the fact that isotopic variations are not related to sediment type convinced us that the pattern accurately reflects conditions at the time of sedimentation and was not strongly affected by postdepositional processes.

Although we are confident of our conclusions, it must be remembered that Spitsbergen is only one small corner of the world. As the Australian expatriate writer Clive James once commented, "He who abandons his claim to be unique is even less bearable when he claims to be representative." Although penned as a critique of autobiography, this wonderful observation neatly summarizes a principal dilemma of geologists. Simply put, how reliable are reconstructions of earth history when the data come from only a few localities? Does the Spitsbergen pattern reflect large-scale changes in late Proterozoic oceans, or is it unique, a signature telling us about one small part of the planet? Only by analyzing geographically widespread sites can we answer this question with certainty.

Data from other continents strongly reinforce the likelihood that Spitsbergen represents the planet as a whole. To begin with, carbon isotopic measurements made more than a decade ago by Manfred Schidlowski and his colleagues at the Max Planck Institute for Chemistry in Mainz also indicate that rates of organic carbon burial increased during the late Proterozoic. Although these scattered samples provide reliable support for the idea of globally en-


NET OXYGEN PRODUCTION
PHOTOSYNTHESIS
$6CO_2 + 6H_2O \leftrightarrow C_6H_{12}O_6 + 6O_2$
RESPIRATION
PHOTOSYNTHESIS
$CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$
BURIAL OF ORGANIC MATTER

OXYGEN LEVELS remain constant generally because most of what is produced by photosynthesis is soon respired back to carbon dioxide and water by other, nonphotosynthetic organisms (*left*). A net production of oxygen occurs, however, when organic remains are buried in sediments and are not respired (*right*). Although most of the excess oxygen thus produced is consumed by weathering, some may accumulate in the atmosphere.

How Rates of Carbon Burial Are Determined

I. Carbon Isotope Ratios

The numeric value of carbon isotope ratios is conventionally reported as $\delta^{13}C$. The number represents the difference between the ratio of ^{13}C to ^{12}C found in a given sample and the ratio that exists in a universal standard, expressed as a per mill (‰, or number of one-thousandths) deviation from the standard. The letters PDB refer to the standard, which is based on a fossil mollusk shell from the Pee Dee Formation, a Cretaceous deposit in South Carolina.

$$\delta^{13}C = \frac{{}^{13}C/{}^{12}C_{\text{sample}} - {}^{13}C/{}^{12}C_{\text{standard}}}{{}^{13}C/{}^{12}C_{\text{standard}}} \times 10^{3}\ (‰,\ \text{PDB})$$

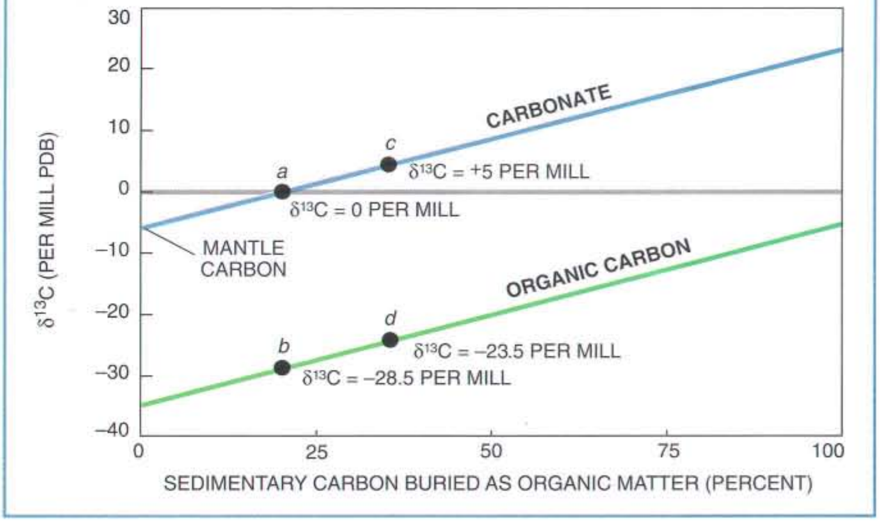
II. Rates of Organic Carbon Burial

Carbon isotope ratios provide useful estimates of rates of organic carbon burial during the geologic past. The reason is that variations in the carbon isotope composition of the world's oceans are determined principally by changes in the burial rates of organic matter. Consequently, by measuring $\delta^{13}C$ values over time, information about increasing or decreasing rates of organic carbon burial can be obtained.

In the accompanying graph, which was devised by John Hayes of Indiana University, the percentage of carbon buried at a given time as organic matter (rather than deposited as carbonate minerals) is shown on the horizontal axis. The ratio of ^{13}C to ^{12}C, expressed as $\delta^{13}C$, is shown on the vertical axis.

Carbon entering the oceans from continental weathering or hydrothermal ridges in the seafloor has an isotopic composition of about −5.5 per mill, similar to that of mantle carbon (the ultimate source of carbon found at the earth's surface). Because the total number of ^{13}C and ^{12}C atoms leaving the oceans through sedimentation must equal the number entering, isotopic compositions for carbonate and organic carbon will vary along two diagonal lines, according to the proportion of organic matter and carbonate entering the sediments. The lines for carbonate carbon and organic carbon are set apart from each other by 28.5 per mill, which approximates the degree to which photosynthesis enriched organic carbon in ^{12}C during the late Proterozoic.

For example, if 20 percent of carbon were buried in the form of organic matter, the value of ^{13}C in carbonates from this period would be about 0 per mill (*a*), whereas the value of $\delta^{13}C$ in organic matter would be about −28.5 per mill (*b*). If the proportion of carbon buried as organic matter were to double, then the $\delta^{13}C$ values for carbonate carbon and organic carbon would shift to about 5 per mill (*c*) and −23.5 per mill (*d*), respectively. Thus, the high $\delta^{13}C$ values recorded in late Proterozoic carbonates and organic matter signal unusually high rates of organic carbon burial during much of this interval.



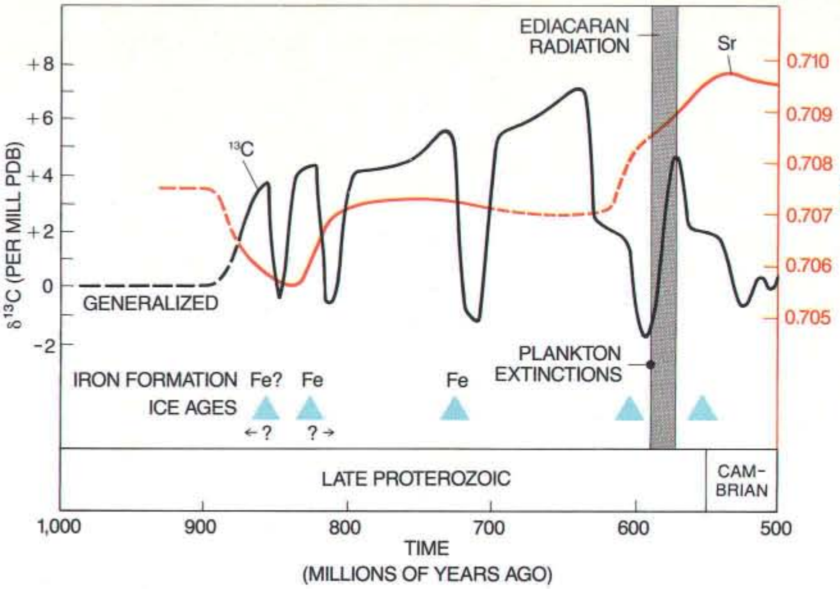
hanced organic carbon burial, their stratigraphic resolution is not sufficient to show the fine-scale changes over time that are demonstrated at Spitsbergen.

Recently Hayes, Kaufman and I found carbon isotopic profiles like those of Spitsbergen in late Proterozoic rock sequences from southern Africa and northwestern Canada. The data strongly imply that high rates of organic carbon burial are part of a global phenomenon, setting the late Proterozoic apart from older as well as younger periods in earth history. To explain such unusually high rates of carbon burial and relate them to early animal evolution, we must consider other features of the late Proterozoic.

Sediments deposited 600 to 850 million years ago include two unusual rock types. One is iron formation, a sediment made principally from silica and iron-bearing minerals precipitated from seawater. Although iron formations are common in Archean and early Proterozoic basins that are 1.9 billion years or older, they are otherwise unknown in younger sediments. Late Proterozoic iron formations occur on five continents in association with the other distinctive rocks of this era: tillites and related sediments deposited by glaciers.

Such an association has provided critical insights into late Proterozoic environmental change. Although the oldest-known continental ice sheets formed between 2.3 and 2.4 billion years ago, major glaciations did not recur until the late Proterozoic. At least four major ice ages occurred between 600 and 850 million years ago as the earth's climate fluctuated between greenhouse and icehouse conditions. One of them, the Varanger ice age of about 600 million years ago, was probably the most severe in earth history. It is clear that the planet was undergoing dramatic physical changes during the period immediately preceding the Ediacaran radiation. An important clue to the puzzle is our finding that the short interval of ^{13}C depletion in late Proterozoic sediments coincided with periods of glaciation and iron formation.

Another clue exists in the form of strontium. Like carbon, strontium occurs in several isotopic forms, of which two—^{87}Sr and ^{86}Sr—are of concern here. In contrast to carbon, however, the ratio of these two isotopes in seawater (and in carbonates precipitated from seawater) depends on continental erosion (which generally supplies strontium in a high ^{87}Sr-to-^{86}Sr ratio) and on hydrothermal input associated with the



KEY FEATURES of late Proterozoic history are shown above. The overall pattern of carbon isotopic variation (*black*) fits well with that of unusually low strontium isotope ratios in seawater (*red*), whereas marked fluctuations within the carbon curve correspond to ice ages and iron formations. These events culminate in the appearance of the Ediacaran animals some 580 million years ago.

spreading of ocean ridges (which typically provides a low ^{87}Sr-to-^{86}Sr ratio).

Ján Veizer of the University of Ottawa has measured the isotopic composition of strontium in carbonates that are 600 to 850 million years old and found the ratio of ^{87}Sr to ^{86}Sr in them to be unusually low. He concluded the late Proterozoic must have been a time of anomalously heightened hydrothermal activity. Equally important, Veizer's data show a distinct shift toward higher ^{87}Sr-to-^{86}Sr ratios not long before the Ediacaran radiation.

My Harvard colleagues Stein B. Jacobsen, Louis Derry and Yemane Asmerom and I have found similar strontium ratios in carbonates from Spitsbergen and elsewhere, strengthening support for the idea that unusually strong hydrothermal activity swept the earth during the late Proterozoic. Such a picture agrees with geologic data that suggest the planet also experienced intense tectonic activity, including the incipient breakup of one or more supercontinents and the buildup of mountains, during this time.

It is now clear that the end of the Proterozoic was beset by change. Carbon isotope ratios indicate that high (albeit fluctuating) rates of organic carbon burial prevailed during much of the eon's last 300 million years. Strontium isotope ratios suggest there was strong hydrothermal activity in the oceans, which appears related to continental breakup and mountain building. Finally, the coincidence of increased iron formation, glacial activity and fluctuating carbon isotope ratios suggests the oceans underwent episodic stagnation (accompanied by oxygen depletion in deep waters) at the same time the planet was experiencing considerable climatic change.

Complete understanding of how these phenomena relate to one another remains elusive. Recently, however, James C. G. Walker of the University of Michigan and I devised a computer model to test how such changes may have affected one another. We found that high rates of organic carbon burial, the onset of ice ages and iron deposition can be related to late Proterozoic tectonic events, particularly increased hydrothermal activity.

But our model raised one concern: reduced volcanic gases produced in association with intense hydrothermal activity could have consumed all the oxygen released by carbon burial. Indeed, the high rates of organic carbon burial suggested by late Proterozoic carbon isotope ratios may actually have been associated with a decrease in oxygen levels. (This would explain why animals—if they existed prior to 600 million years ago—would have been tiny.) Fortunately, strontium isotope data indicate that intense hydrothermal activity ended roughly 600 million years ago, and, according to our model, oxygen levels also increased rapidly at this time, which coincides with the diversification of large animals.

Available evidence thus links the Ediacaran radiation to a late Proterozoic increase in atmospheric oxygen. Moreover, these events now seem embedded within an even larger framework of tectonic, climatic and biogeochemical change. My guess is that the fundamental driver of late Proterozoic change was tectonic. Specifically, I think the hydrothermal and volcanic events associated with tectonic activity promoted anomalously high rates of organic carbon burial in late Proterozoic basins. Enhanced burial in turn would have increased the oxidizing potential of the atmosphere and hydrosphere and thus eventually given rise to a more oxygen-rich biosphere. Once the physiological barrier created by a limited oxygen supply was removed, the first microscopic metazoans were free to evolve into the macroscopic forms that quickly came to dominate the animal world.

At present, this hypothesis, like others before it, must be regarded as heuristic rather than gospel. Yet it articulates an explicit set of relations between the earth and its biota and so makes predictions that can be tested by further study. Whether or not my particular view of the late Proterozoic will withstand such testing remains unclear. The rate at which my colleagues and I are surprised by new findings about the Proterozoic world suggests that the fun is not yet over. What is important is that we have begun to ask new questions about evolution on a dynamic earth. In this case, we are starting with a vivid sense that the modern world arose when biogeochemical cycles linked the physical and biological earth in profound change at the end of the long Proterozoic eon.

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SECULAR VARIATION IN CARBON ISOTOPE RATIOS FROM UPPER PROTEROZOIC SUCCESSIONS OF SVALBARD AND EAST GREENLAND. A. H. Knoll, J. M. Hayes, A. J. Kaufman, K. Swett and I. B. Lambert in *Nature*, Vol. 321, No. 6073, pages 832–838; June 26, 1986.

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How the Immune System Learns about Self

The immature immune system produces cells that would attack every tissue in the body. Within the thymus, however, it learns which cells would be harmful, useless or useful

by Harald von Boehmer and Pawel Kisielow

The immune system can be our salvation and our ruin. It protects us from bacteria, viruses and other harmful microorganisms, but it can also reject lifesaving transplants of kidneys, hearts and bone marrow. It will accept organ grafts from an identical twin but reject organs from a complete stranger or even another family member. In such autoimmune diseases as multiple sclerosis, it will attack a healthy tissue as though it were a pathogenic invader. From this behavior we know that the immune system can ordinarily distinguish "self," tissue that is genetically identical to that of the body, from "nonself," genetically foreign material.

Despite 100 years of debate and speculation, the principles and mechanisms of this discrimination process have until recently been obscure. Experimental analyses were hindered by the vast diversity of immunologic cells and receptor molecules, which enable the immune system to recognize the wide variety of self and nonself substances collectively called antigens.

One idea in particular, clonal deletion, has been the center of much controversy. According to this hypothesis, the immune system initially contains cells that have the potential to attack the body's tissues, but these cells are somehow eliminated before they can do any harm. Although the concept is easy to outline, determining whether such cellular deletions actually occur and probing the specifics of how they take place was difficult until the advent of modern genetic technologies.

Using those techniques, we created mice whose immune systems produce only one type of antigen receptor instead of 100 million. Then, by following the development of cells bearing this receptor in various animals, we were able to prove the existence of clonal deletion and to describe, in detail previously impossible, the discrimination between self and nonself. Our improved understanding of the cellular and molecular mechanisms of self-nonself discrimination could eventually lead to more rational medical strategies for correcting such immune disorders as immunodeficiency and autoimmunity and for preventing transplant rejection.

HARALD VON BOEHMER and PAWEL KISIELOW have long been collaborators in the study of *T* lymphocytes. Von Boehmer is professor of immunology at the University of Basel and at the University of Florida at Gainesville; he is also a permanent member of the Basel Institute for Immunology. He received his medical degree from the University of Munich in 1968 and his doctorate in biology from the University of Melbourne in 1974. Kisielow is professor and head of the laboratory of cellular immunology at the Institute of Immunology and Experimental Therapy of the Polish Academy of Sciences in Wroclaw, Poland. In 1971 he received his doctorate from that institute.

To explain what we and other investigators have learned about self-nonself discrimination and the experiments that led us to that knowledge, we must first introduce a few facts about the components and development of the immune system. The immune system of humans and other animals is in large part composed of millions of white blood cells, the lymphocytes. Morphologically, one lymphocyte looks much like another. In reality, each clone, or genetically identical set of cells, differs from all others because it carries several thousand copies of a unique receptor protein on its surface. A receptor can fit an antigen as a lock does a key. Structurally, the receptors consist of a constant part, which is the same on many lymphocytes, and a variable part, which is specific to each lymphocyte and allows the receptor to bind to its antigen.

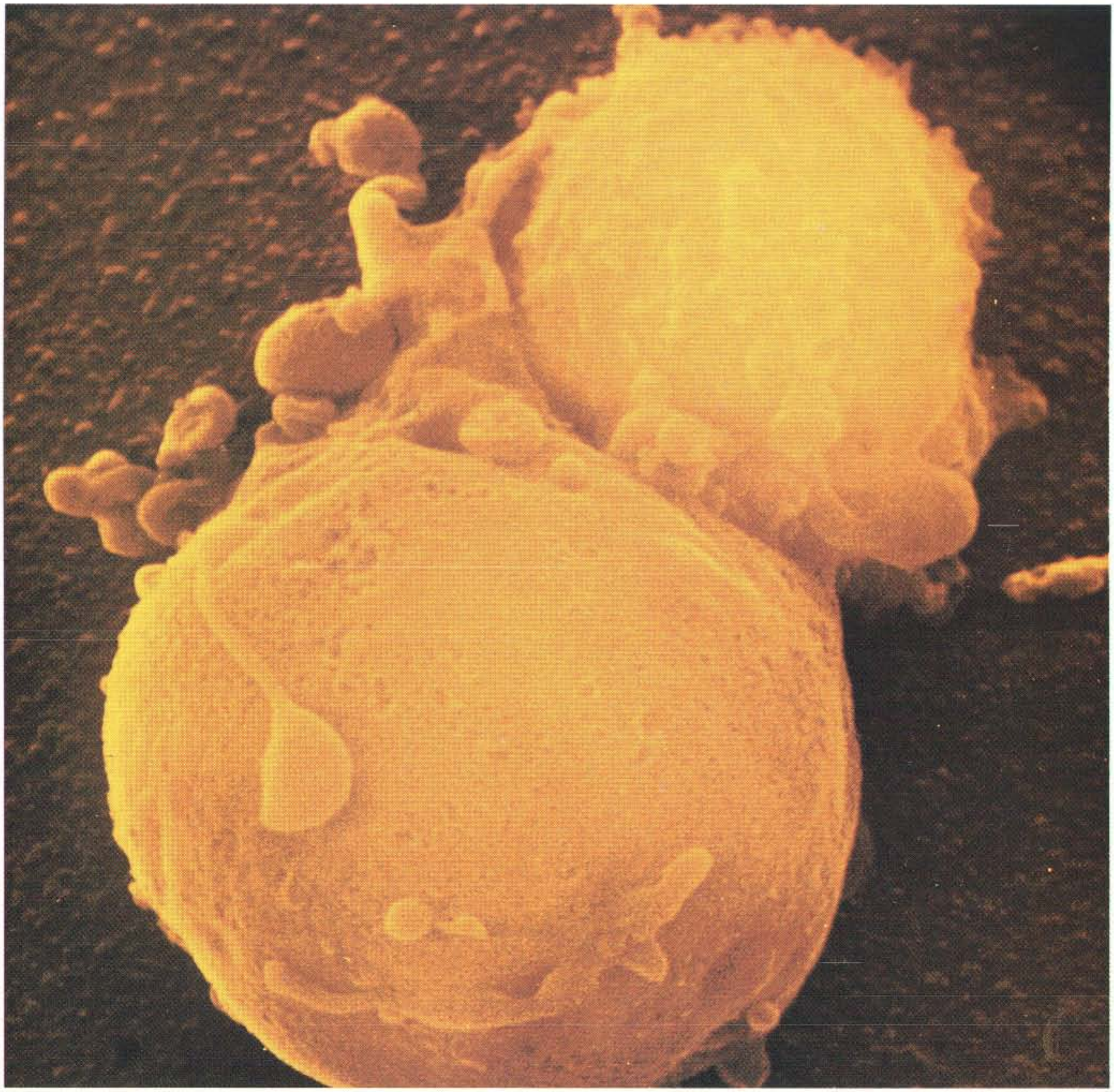
Aside from the differences in their antigen receptors, lymphocytes can also be divided into groups according to their origin and functional role in the immune system. Lymphocytes that mature in the thymus (a spongy gland under the breastbone) are known as *T* cells; those that develop in the bone marrow are *B* cells. Unlike *T* cells, *B* cells are able to secrete their receptors, which circulate in the blood as antibodies. *T* cells respond to antigen in other ways, and on that basis they can be further subdivided into two classes.

The most aggressive lymphocytes are the cytotoxic, or "killer," *T* cells. Their main task is to screen other cells for signs of viral infection and other abnormalities, such as development into cancer cells. Viruses hide and multiply inside a host cell until it bursts, releasing thousands of new virus particles to infect other cells. The immune system can usually interfere with this vicious circle, even though the viruses are hidden, because cells constantly degrade proteins, including viral proteins, into fragments called peptides. The peptides are transported to the cell surface and presented to the immune system. The antigen receptors of killer *T* cells allow them to recognize the viral peptides, which signal that a cell must be destroyed as unhealthy.

The astonishing mechanism that transports and presents peptides has been revealed in pioneering studies by Howard M. Grey of the National Jewish Center for Immunology and Respiratory Medicine in Denver and by Emil R. Unanue of Washington University School of Medicine in St. Louis, as well as in more recent crystallographic work by Pamela J. Bjorkman and Don C. Wiley of Harvard University. They have shown that most peptides bind to major histocompatibility complex (MHC) molecules inside a cell. The molecules are of two types: class I MHC, which displays peptides from proteins made inside the cell, and class II MHC, which displays peptides from proteins that have entered the cell from the outside (such as bacterial toxins).

Both kinds of MHC molecules carry peptides to the cell surface and present them to prekiller (unactivated) *T* lymphocytes. When a prekiller *T* cell bearing a correctly fitting receptor encounters an antigen-MHC complex, the *T* cell divides repeatedly; all the daughter cells eventually become active killer *T* lymphocytes with the same receptor and the power to destroy infected cells. Killing the cells deprives a virus of life support and makes it accessible to antibodies, which can finally eliminate it.

We still do not know exactly how killer *T* cells recognize peptides, but we have a good idea which molecules are involved. Antigen recognition by killer *T* lymphocytes is peculiar because the cells are specific for both the peptide and the peptide-presenting MHC molecule. This dual specificity was first recognized in killer *T* cells by Rolf M. Zinkernagel and Peter Doherty in 1974, who were then working at the Australian National University. At first, it was not clear whether the dual specificity was a property of a single receptor or of two or whether it might be the result of two different lymphocytes working in concert. Then, in 1978, Hans Hengartner, Werner Haas and one of us (von Boehmer) of the Basel Institute for Immunology isolated a single killer *T*



KILLER *T* CELL (*upper right*) attacks a tumor cell and destroys it. To fend off disease, *T* cells and other parts of the immune system must distinguish the "self" of the body from the "nonself" of abnormal cells. Investigators have recently discovered how the immune system selects for receptor-bearing *T* cells that can discriminate between types of cells.

cell and propagated it alone in tissue culture. The resulting clone of identical cells still exhibited the original specificity for peptide and MHC molecules, indicating that a single *T* cell had dual specificity. For several years, that was all we knew about the problem.

During the mid-1980s, the long, controversial search for the elusive receptor of killer *T* cells culminated in the discovery of the genes and proteins of the alpha-beta *T* cell receptor (TCR). Many laboratories contributed to that work, including those of Mark M. Davis, then at the National Institutes of Health in Bethesda, Tak W. Mak of the Ontario Cancer Institute in Toronto, James P. Allison, then at the University of Texas at Dallas, Ellis L. Reinherz of Harvard Medical School and Philippa C. Marrack and John W. Kappler of the National Jewish Center for Immunology and Respiratory Medicine. The newly discovered receptor molecule consisted of one alpha and one beta polypeptide chain, each encoded by a separate gene.

In 1986 Zlatko Dembic, Michael Steinmetz, Haas and one of us (von Boehmer) of the Basel Institute for Immunology transferred the alpha and beta TCR genes from one *T* cell clone into a second clone with a different specificity. The resulting *T* cells had the specificities of both the donor and the recipient cells. A single molecule—the alpha-beta TCR—therefore determined a cell's specificity for both one peptide and one MHC molecule.

By itself the binding of the alpha-beta TCR to a peptide and an MHC molecule is usually insufficient to change a prekiller *T* cell into a killer *T* cell. Full activation requires the binding of another molecule, the CD8 receptor. That receptor, which is the same on all killer *T* cells, also binds to MHC molecules but at a site different from that of the alpha-beta TCR. The CD8 protein was discovered in 1968 by Edward A. Boyse and his colleagues at the Sloan-Kettering Institute for Cancer Research in New York City. In 1974, while at Sloan-Kettering, Hiroshi Shiku and one of us (Kisielow) discovered that the CD8 protein was unique to killer *T* cells and could be used to distinguish them from other lymphocytes.

The function of the CD8 coreceptor became apparent in 1987. By transferring a CD8 gene into a CD8-negative killer cell line, Dembic and one of us (von Boehmer) showed that the CD8 coreceptor is actively involved in antigen recognition by killer *T* cells. At about the same time, Frank Emmrich and Klaus Eichmann of the Max Planck Institute for Immunology in Freiburg discovered that a killer *T* cell is activated most effectively when an alpha-beta TCR and a CD8 coreceptor are bound by the same molecule.

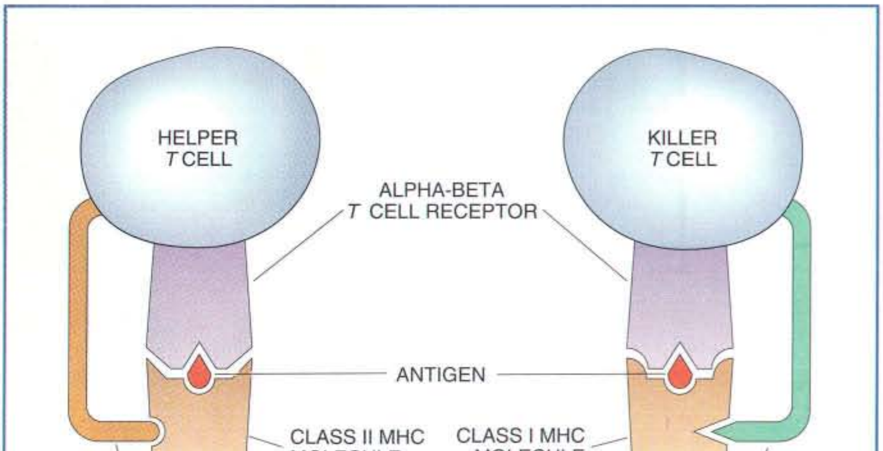
A second class of *T* lymphocytes, the helper *T* cells, also has an alpha-beta TCR and an invariant coreceptor that work together to activate the immunologic defense. The TCR on the helper cells is encoded by the same alpha and beta genes that make those of the killer *T* cells. The invariant coreceptor of the helper cells is the CD4 protein, however, not CD8. Whereas alpha-beta TCRs and CD8 coreceptors on killer *T* cells bind to class I MHC molecules and peptides from proteins made inside cells, alpha-beta TCR and CD4 coreceptors on helper *T* cells bind to class II MHC molecules and peptides from proteins ingested by cells.

Helper *T* cells also play a different role: they cooperate with *B* cells in the antibody response to antigens such as bacterial toxins. After a toxic protein is released into the bloodstream, it is taken up by macrophages, cells that nonspecifically scavenge and ingest various substances. *B* cells, too, ingest toxin molecules that have bound to the unique antibody-type receptors on their surfaces.

Inside the macrophages and *B* cells, the toxin is degraded, and its peptides are then transported to the surface by class II MHC molecules. Once the alpha-beta TCRs and the CD4 coreceptors of a prehelper *T* cell are bound by the same MHC molecules on a presenting cell, the *T* cell starts to divide and produces active helper *T* cells. (Macrophages are particularly potent at activating the cells.) The active helper *T* cells produce factors called interleukins that further stimulate the *B* cells to divide and to secrete large amounts of their specific antibodies, which circulate freely in the blood, bind to the toxin and neutralize it.

The tremendous diversity of alpha-beta TCRs and MHC molecules is the key to the selective activity of the *T* cells; the patterns and causes of that diversity therefore bear directly on self-nonself discrimination. The genes encoding the variable part of the TCR are inherited from our parents not as a continuous stretch of genetic information but instead as little pieces or segments that combine randomly in the developing lymphocytes. That recombination mechanism creates the genes for 100 million or more different TCRs in an individual. The variability seen in MHC molecules is different; although many different MHC genes are present in the population, one individual will have only two genes for each type of MHC molecule.

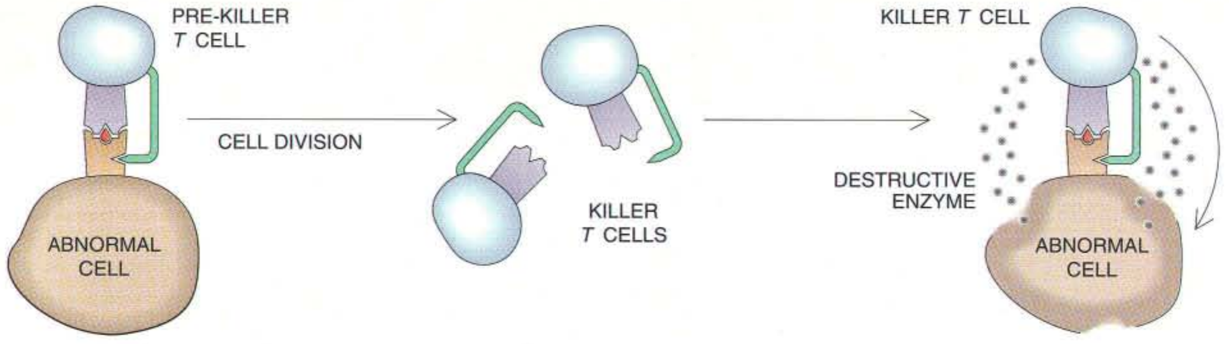
Because TCRs are generated purely by chance, without regard for which MHC molecules and peptides are in the body, one can imagine that, for any individual, certain receptors will be



RECEPTOR COMPLEXES on *T* cells govern their activity. Both killer and helper cells have alpha-beta *T* cell receptors (TCRs) that can recognize antigens displayed by major histocompatibility (MHC) proteins on cell surfaces. Coreceptor molecules on killer and helper cells bind to different classes of MHC molecules.

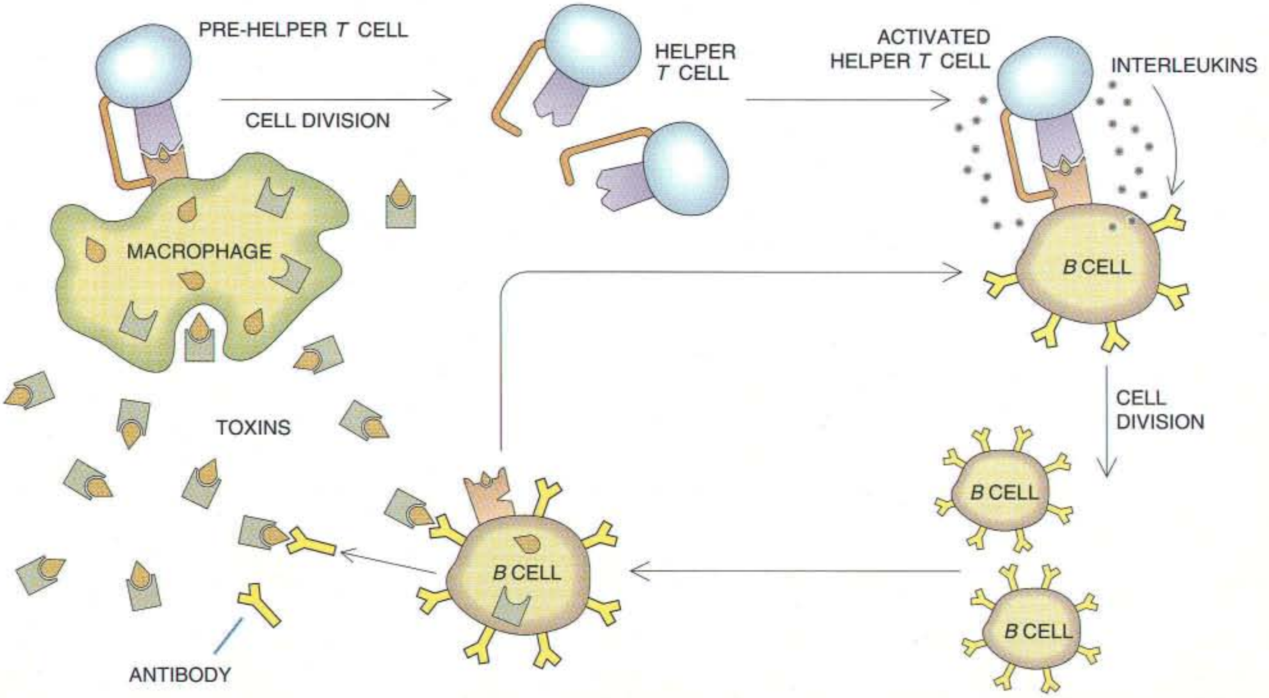
How Killer *T* Cells Act

Killer cells recognize foreign antigens displayed by abnormal cells, which they destroy with enzymes.



How Helper *T* Cells Act

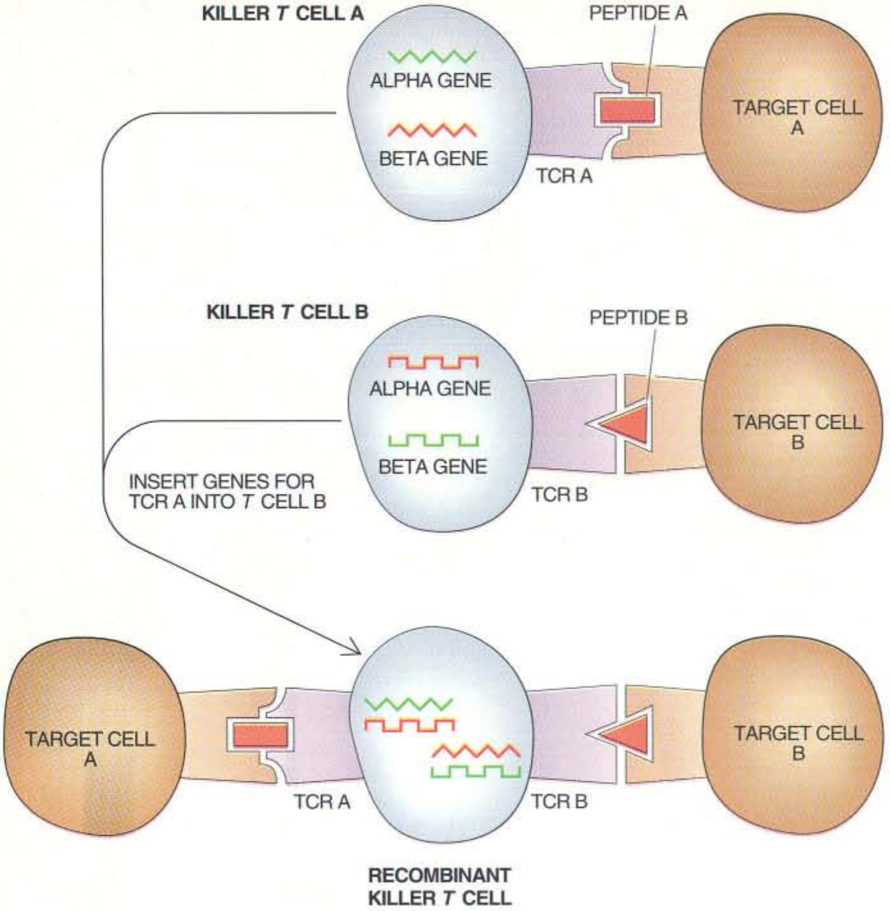
Helper *T* cells respond to antigens presented by macrophages and *B* cells, which ingest bacterial toxins and other foreign antigens in the blood. The helper cells then multiply and secrete compounds called interleukins that encourage *B* cells to multiply and release disease-fighting antibodies.



useful, some will be useless and still others harmful. Useful receptors are those that can help defend the body by binding to nonself-peptides from viral or bacterial proteins presented by self-MHC molecules. Useless receptors are ones that cannot recognize any peptides when presented by self-MHC molecules. Harmful receptors would bind to self-peptides presented by self-MHC molecules; lymphocytes with such receptors might attack the body's own tissue. Self-nonself discrimination by the immune system is therefore a question not only of how harmful *T* cells are prevented from destroying the body but also of how the wasteful accumulation of useless *T* cells is prevented.

An answer to the problem of harmful *T* cells was proposed first in 1948 by Frank J. Fenner and Sir F. Macfarlane Burnet of the Walter and Eliza Hall Institute of Medical Research in Melbourne and later in 1963 by Joshua Lederberg, then at the University of Wisconsin at Madison. They suggested that harmful cells were deleted or removed early.

The assumption underlying their clonal deletion hypothesis was simple: lymphocytes with antigen receptors pass through two phases of development characterized by radically different responses to antigen binding. In the first phase, binding with an antigen would kill an immature lymphocyte; during the second phase, antigen binding would activate the cell rather than kill it. Because self-peptides are always present, lymphocytes that have receptors for self-antigens would be exposed to them and deleted early in development, thus leaving only the cells that have receptors for nonself-antigens. The



TRANSFER OF THE GENES for the antigen receptor will alter the reactivity of the recipient cell. If the genes for a unique TCR are extracted from one *T* cell and inserted into a *T* cell with a different TCR, the resulting cell will make both receptors and respond to both antigens recognized by the donor and recipient cells.

latter cells could mature further and could be stimulated when foreign antigens enter the body.

The immune system's selective accumulation of useful *T* cells has been studied by several investigators, including Jonathan Sprent and Michael J. Bevan of the Research Institute of Scripps Clinic, Zinkernagel and one of us (von Boehmer). They have raised the possibility that *T* cells with receptors capable of binding to self-MHC molecules proliferate and accumulate preferentially in the lymphoid organs. Cells that could not recognize self-MHC molecules would not expand their numbers.

Both hypotheses initiated many experiments and even more arguments. The clonal deletion hypothesis was favored and disfavored by approximately equal numbers of scientists. In the 1960s and 1970s Sir Gustav J. V. Nossal of the Walter and Eliza Hall Institute, Melvin Cohn of the Salk Institute and others stood on the "pro-deletion" side, whereas Richard K. Gershon of the Yale University School of Medicine, Niels Jerne of the Basel Institute for Immunology and others took the "contra-deletion" side. Experiments that could conclusively settle the matter could not be done, because at that time the nature of TCRs was unknown and because reagents for identifying the specificity of TCRs (such as monoclonal antibodies) were not available. Investigators could examine only whether antigen-specific *T* cells could be activated under certain experimental conditions. Such tests could not distinguish *T* cells that were silent (not induced) from those that might be absent (physically eliminated).

The same problem dogged experiments for testing whether some mechanism preferentially expanded or selected clones of useful *T* cells. Sprent, Zinkernagel, one of us (von Boehmer) and others insisted on such a mechanism, whereas Polly Matzinger of the University of California at San Diego, Leroy E. Hood of the California Institute of Technology, Philippe Kourilsky of the Pasteur Institute in Paris and others contested it—again on the basis of inconclusive experiments. As a result, we had decades of hot debate.

By the mid-1980s the nature of TCRs was disclosed, and it became possible to raise TCR-specific antibodies. Before investigators could perform conclusive experiments on self-nonself discrimination, however, they had to cope with another obstacle: it was impossible to follow the development of the few *T* cells bearing any one particular receptor because they represented only a tiny fraction of all the lymphocytes in a normal animal. The few cells of interest would become lost in the crowd.

For that reason, in 1985 one of us (von Boehmer) decided to study self-nonself discrimination in TCR transgenic mice. Transgenic mice carry genetic material that has been introduced artificially. The fundamental technique that we used was developed in the mid-1970s by Ralph L. Brinster of the University of Pennsylvania and Rudolph Jaenisch, then at the Salk Institute. We transferred the TCR genes from one *T* cell clone into fertilized mouse eggs. The mice that developed from those eggs had integrated the added genes into their own genome and expressed them by making the encoded TCR.

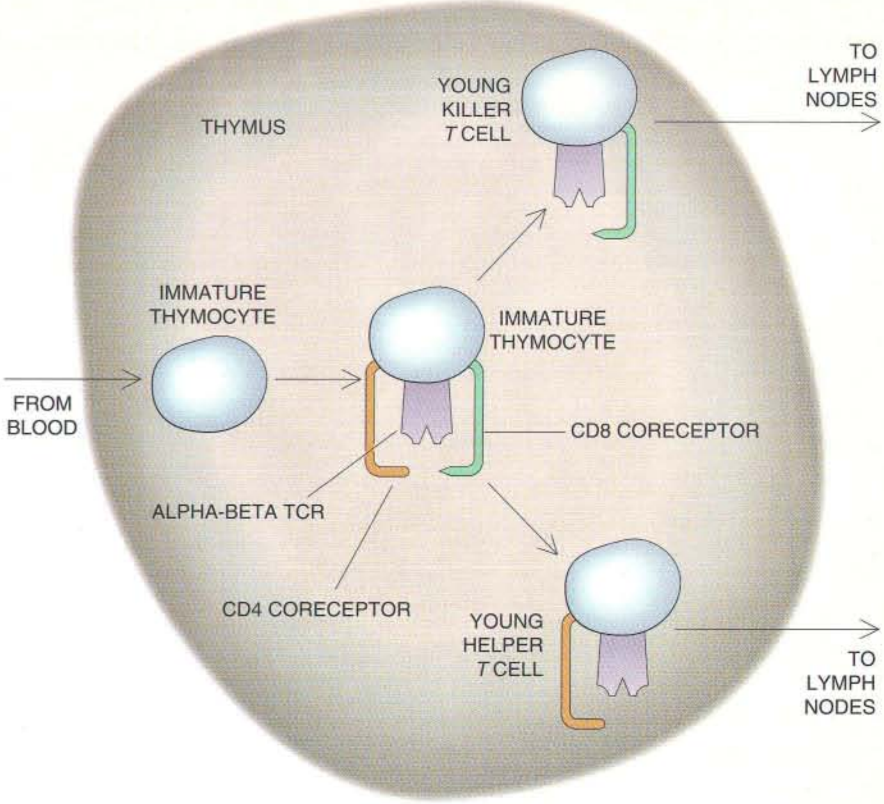
Because we hoped to create a mouse that made the transgenic TCR exclusively, we used mice that had recently been discovered by Melvin Bosma of the Fox Chase Cancer Center in Philadelphia. Those mice had a genetic defect, severe combined immune deficiency (SCID), which resulted from the inability to combine antigen-receptor gene segments properly. Consequently, they could not produce any antigen receptors of their own. By introducing one functional alpha and one beta TCR gene into a SCID mouse, we could obtain an animal that expressed only the transgenic TCR.

With the help of Yasushi Uematsu of Steinmetz's laboratory at the Basel Institute for Immunology, Anton Berns of the Netherlands Cancer Institute in Amsterdam and Horst Bluthmann of Central Research Units, F. Hoffman-La Roche & Co., we produced such a mouse strain. With these mice we could conclusively address many crucial questions about self-nonself discrimination by the immune system.

We had chosen a TCR specific for the HY peptide, an intracellular peptide that is present in male mice but absent in females. This peptide, we knew, was presented by class I MHC molecules called D^b. The alpha and beta genes encoding the receptor were isolated from a clone of killer *T* cells and were introduced into the SCID mice. By breeding our transgenic SCID mice in various permutations, we could produce animals in which all the developing lymphocytes would carry the transgenic TCR and would be predictably harmful, useless or potentially useful. In male mice that had D^b MHC molecules, the transgenic TCR would be harmful (it would bind with the self-peptide HY and the self-MHC). In females that lacked D^b, the TCR would be useless because it could not bind to the MHC molecules. The TCR would be useful in females that had D^b and could present HY as a nonself-peptide.

We set out to analyze the fates of the harmful, useless and useful T cells in each of these cases. Our analysis was crucially dependent on an antibody against the transgenic TCR that was made by Hung Sia Teh of the University of British Columbia in Vancouver, who spent a sabbatical in our laboratory. Without that antibody we could never have been sure that we were analyzing the development of cells expressing the transgenic TCR.

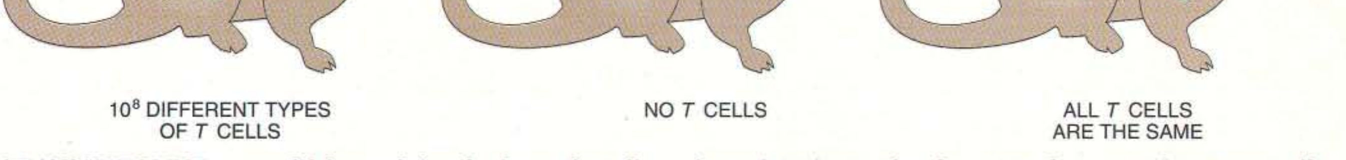
The results showed that when the TCR was harmful—that is, in male transgenic SCID mice carrying both HY peptide and D^b MHC molecules—the thymus contained few immature thymocytes (the precursors of *T* cells) and no mature helper or killer *T* cells at all. Because any mature *T* cells would have been harmfully self-reactive, they were deleted before they could become dangerous. That result was entirely consistent with the clonal deletion hypothesis. Follow-up experiments by our student Wojciech Swat of the Institute of Immunology and Experimental Therapy in Wroclaw, Poland, have shown that physical deletion rather than arrested development causes the absence of the immature thymocytes.



T CELL DEVELOPMENT occurs principally in the thymus gland. Immature cells entering the thymus do not initially bear a *T* cell receptor or either type of coreceptor. Later the slightly more mature thymocytes express all three molecules. Depending on its experiences in the thymus, a *T* lymphocyte eventually stops making one of the coreceptors and becomes either a killer cell or a helper cell.

When the TCR was useless, as it was in female transgenic SCID mice lacking D^b MHC molecules, immature thymocytes were present, but mature helper and killer *T* cells were absent. That observation indicated that useless cells incapable of recognizing and interacting with the self-MHC molecules do not mature; they die after a short life span.

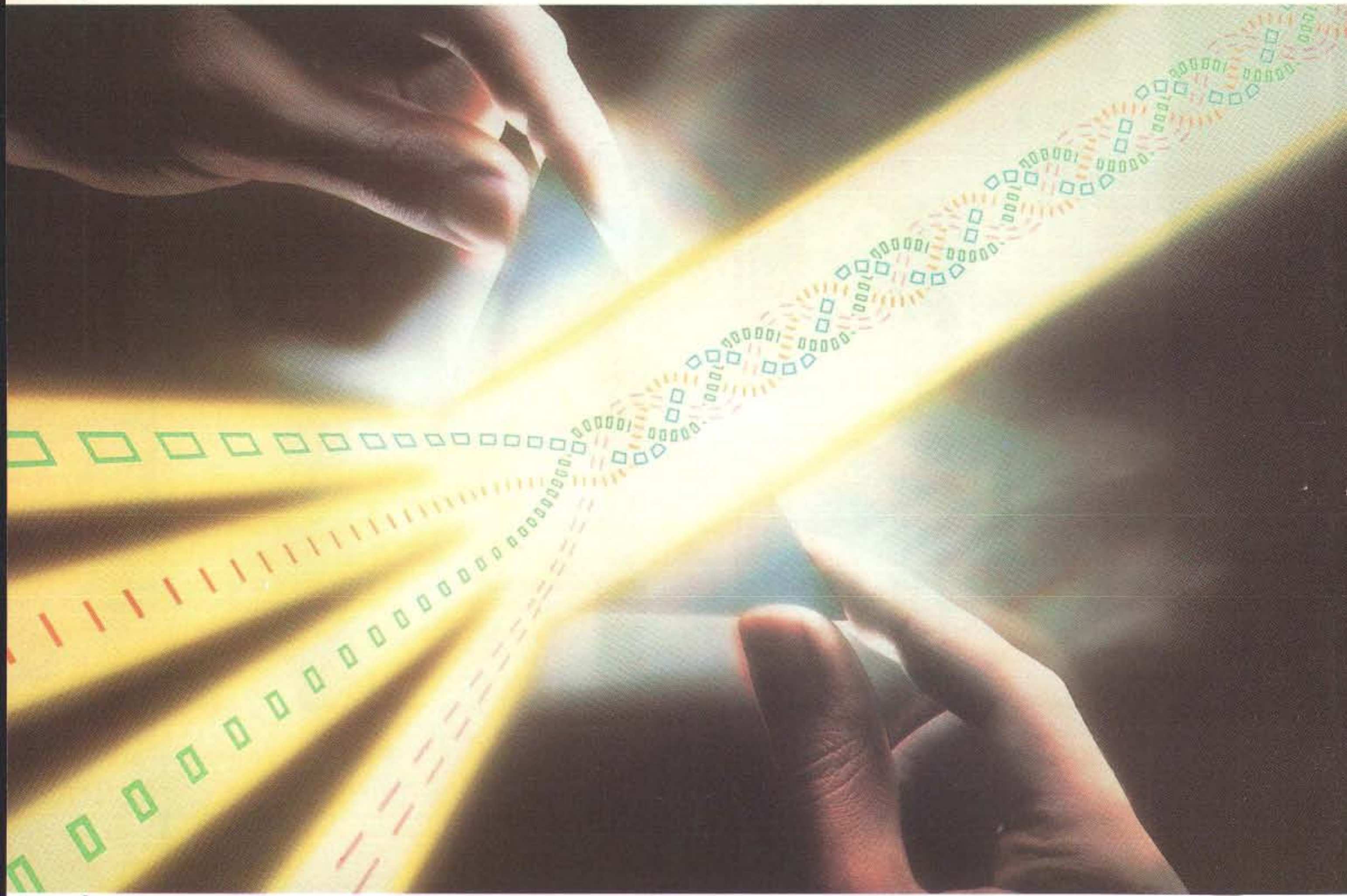
Finally, when the TCR was potentially useful, as in the female mice carrying class I D^b MHC molecules, we found immature thymocytes and mature killer *T* cells but no mature helper *T* cells. That result holds two implications. First, the binding of the alpha-beta TCR to MHC molecules in the absence of the antigen peptide rescues immature cells from death and induces maturation. Second, the specificity of the alpha-beta TCR for


NORMAL MOUSE
SCID MOUSE
T CELL RECEPTOR TRANSGENIC SCID MOUSE
10^8 DIFFERENT TYPES OF T CELLS
NO T CELLS
ALL T CELLS ARE THE SAME

TRANSGENIC MICE are useful for studying the fates of *T* cells bearing specific receptors. Normal mice produce *T* cells with so many different receptors that it is difficult to follow one set of cells. Mice that have the severe combined immune deficiency (SCID) mutation, however, do not produce any *T* cells. If the genes for one *T* cell receptor are inserted into a SCID mouse egg, all the *T* cells in the resulting mouse will have the same receptor and meet the same developmental end.

Ericsson Transport Network Architecture

Laying the foundations of a responsive public network



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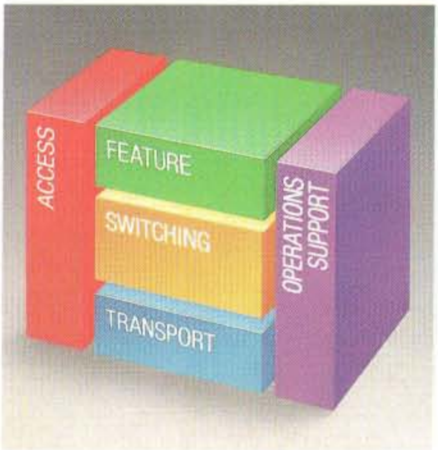

At the sides of the model are the access systems; and an integrated set of operations support systems to manage and control all the layers of the network model.

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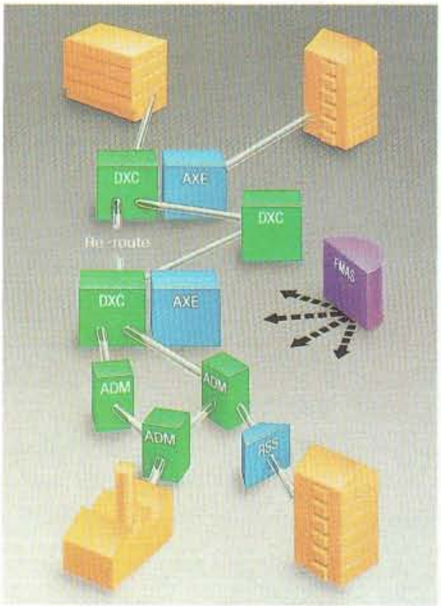

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class I or class II MHC molecules determines whether a developing *T* cell will become a helper cell or a killer cell. Because the genes for the TCR that we had inserted came from a killer *T* cell clone, all the *T* cells in our transgenic SCID mice became killer cells.

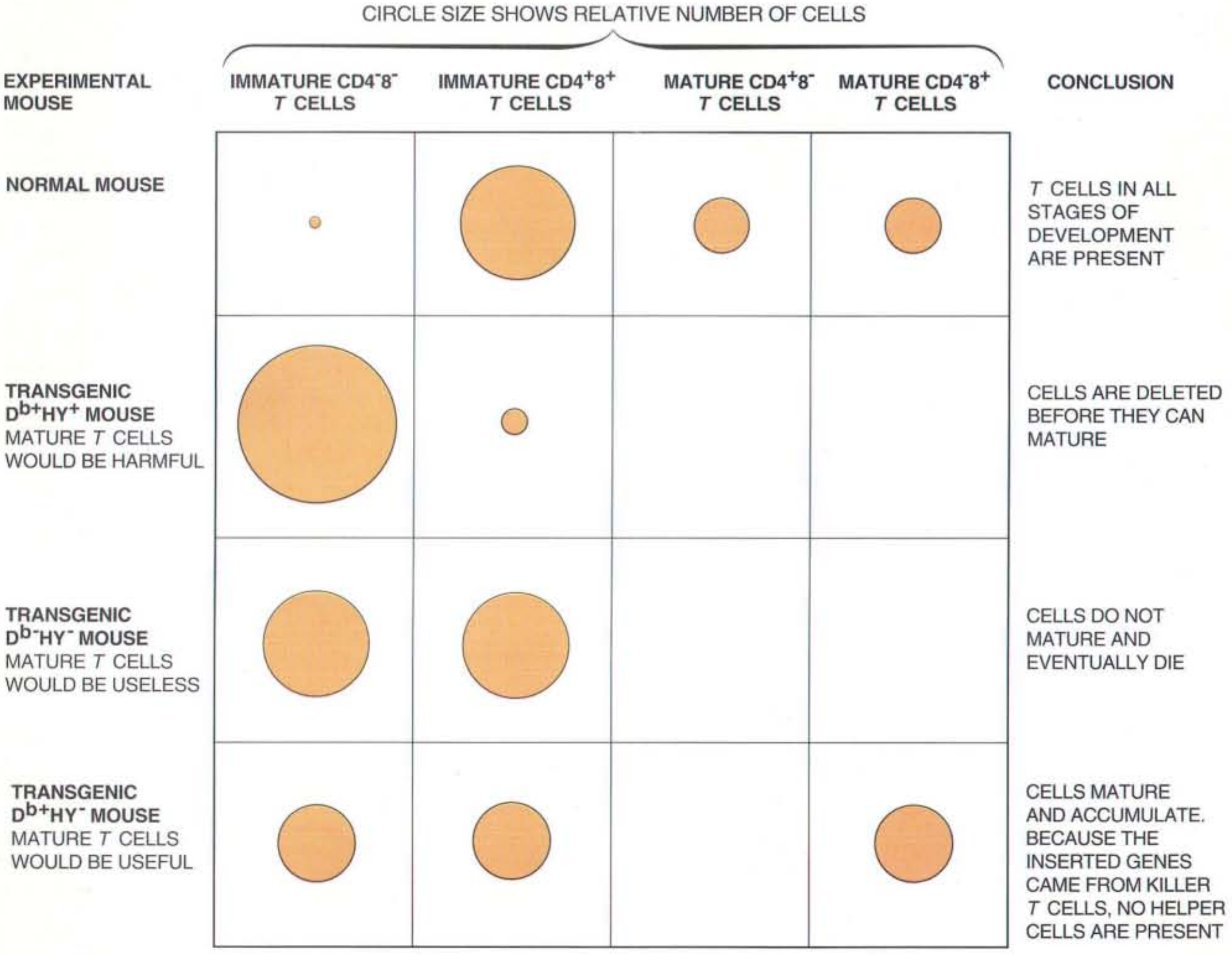
By extrapolating our results to receptor selection in normal, nontransgenic animals, we arrived at the following picture of self-nonself discrimination by the immune system. Immature thymocytes express a wide variety of antigen receptors, which are generated through random combinations of TCR gene segments and through random pairings of various alpha and beta TCR chains. If the receptor on one of these cells does not bind to any molecules in the thymus, the cell is useless and dies after about three days. If the receptor binds in the thymus to both the peptide and the MHC molecule, the cell is destroyed because it is harmful. If the receptor binds to MHC molecules in the absence of its antigen peptide, the cell is potentially useful and is therefore selected for further maturation. Depending on whether the receptor binds to a class I or class II MHC molecule, the selected cell will become either a killer or a helper *T* lymphocyte.

Helper and killer cells patrol the body's lymph nodes, spleen and other peripheral lymphoid organs. After they leave the thymus, they react differently when their receptor binds to a peptide and an MHC molecule: the binding of a receptor to both molecules results in *T* cell activation and the generation of effector cells. Thus, the immune system learns to distinguish self from nonself by screening lymphocytes: the useful are selected, the useless are neglected and the harmful are rejected.

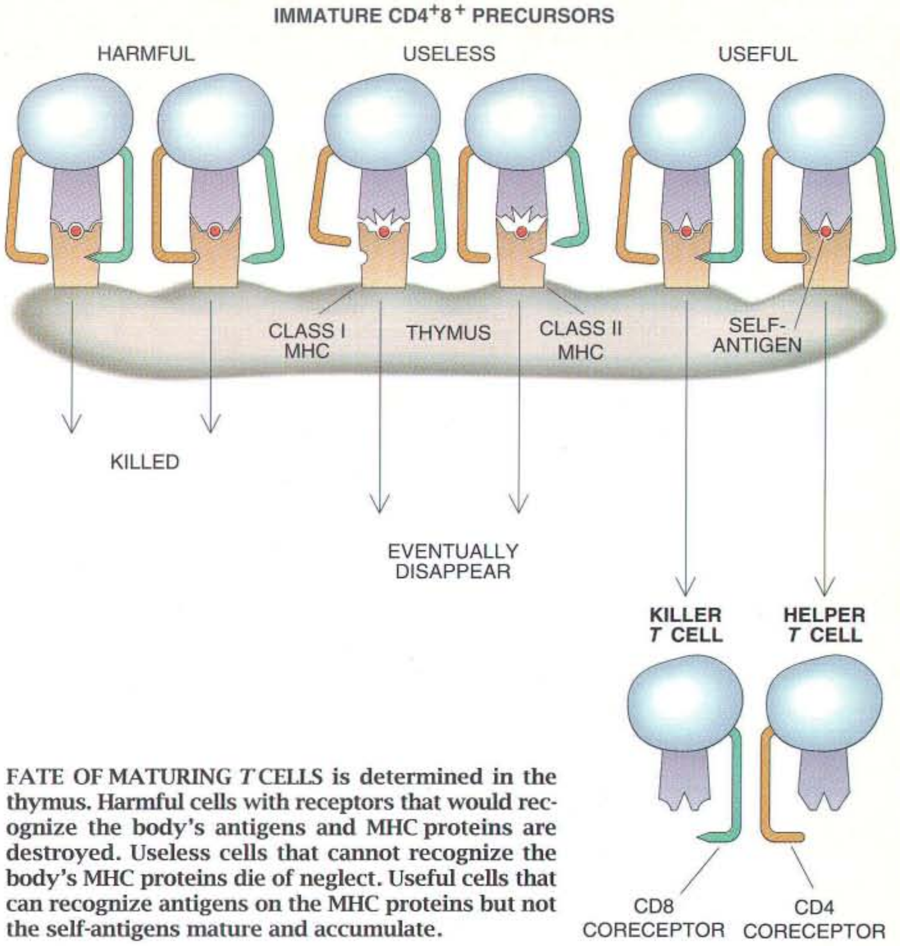
There is now good evidence that the deletion of immature harmful cells also occurs in normal mice. As we have already mentioned, it is difficult to follow the fate of cells with one specific receptor in normal animals. Yet Kappler and Marrack have found that certain molecules called superantigens will bind with many different TCRs and also with class II MHC molecules. Superantigens do not bind to MHC molecules and TCRs at the same sites as peptide antigens. Nevertheless, using superantigens in normal mice, Kappler and Marrack, Zinkernagel and H. Robson MacDonald of the Ludwig Institute of Cancer Research in Lausanne have

A Test of Clonal Deletion

To determine the fate of different *T* cells, the authors created transgenic SCID mice in which all the *T* cells had the same receptor. That receptor would only recognize the HY peptide as presented by the D^b MHC molecule. Depending on a particular mouse's biochemical makeup, such *T* cells would be either harmful, useless or useful. Observations of which cells survived in the thymuses supported the clonal deletion theory—that harmful *T* cells are eliminated before they can mature, whereas useful cells are preserved.



obtained data that are compatible with our studies of TCR transgenic mice. Dennis Loh of Washington University School of Medicine, Davis, now at Stanford University, Stephen Hedrick of the University of California at San Diego and Zinkernagel, using different TCR transgenic mice, have also come to similar conclusions and have extended our results.



FATE OF MATURING *T* CELLS is determined in the thymus. Harmful cells with receptors that would recognize the body's antigens and MHC proteins are destroyed. Useless cells that cannot recognize the body's MHC proteins die of neglect. Useful cells that can recognize antigens on the MHC proteins but not the self-antigens mature and accumulate.

Most investigators agree that clonal deletion is probably not the only way to silence harmful *T* cells. In our minds, the question never was whether clonal deletion was the only mechanism but whether it existed at all. We now know that deletion is most easily induced in immature thymocytes, which implies that only those peptides produced in the thymus or carried there can induce deletion. If all self-peptides were present in sufficient quantity to induce deletion, autoimmunity would not exist. The fact that it does indicates that the deletion mechanism of self-nonself discrimination is not perfect and that other processes probably do exist.

Although ample circumstantial evidence supports the existence of "suppressor" *T* cells that prevent other *T* cells from becoming active, we have as yet no conclusive evidence on how these cells operate. Marc K. Jenkins, Ronald H. Schwartz and B. J. Fowlkes of the National Institutes of Health, David Lo of the Scripps Clinic and Jacques Miller of the Walter and Eliza Hall Institute have demonstrated that certain peptides, when presented on cells other than *B* cells and macrophages, can induce anergy in *T* cells: anergic *T* cells do not die, but they are unresponsive to antigenic stimulation. Despite some progress in understanding self-nonself discrimination by mature *T* cells, we are still far from achieving the clinical goal of specifically silencing them. Achieving that goal would make organ transplantation far more successful than it is today.

Our experiments were designed to probe the mechanisms of self-nonself discrimination and not to solve the problem of organ transplantation or autoimmunity. Yet we may ponder how the results might bear on those problems. Some forms of autoimmunity are almost certainly caused by the recognition of antigens that are not present in the thymus and that therefore do not delete *T* cells. That is seemingly the case with myelin basic protein, which is normally sequestered in the nervous system; injections of myelin basic protein into some animals can induce experimental allergic encephalomyelitis (EAE), a disease akin to multiple sclerosis in humans. Many investigators also suspect that antigens found on insulin-producing pancreatic islet cells do not reach the thymus. If these antigens become the targets of autoimmune *T* cells, the result could be diabetes.

Of course, it would be tempting to try to prevent autoimmune diseases by identifying the organ-specific antigens involved and introducing them into the thymus to delete the offensive *T* cells. Hartmut Wekerle of the Max Planck Institute for Psychiatry in Munich and Eli E. Sercarz of the University of California at Los Angeles have performed such experiments by injecting relatively high doses of myelin basic protein into neonatal mice. The procedure did protect the animals from developing EAE after subsequent injections.

Ali Naji and his co-workers at the Hospital of the University of Pennsylvania in Philadelphia have explored the application of thymic tolerance mechanisms to organ transplantation. They implanted foreign pancreatic islets in the thymuses of rats; subsequent grafts of the islet tissue were permanently accepted by the animals.

It remains to be shown whether the tissue-specific antigens in the thymus caused the deletion of the developing, potentially harmful *T* cells, but at present that is the most logical explanation. These experiments do not provide an immediate solution to the problem of autoimmunity and transplantation. They do nonetheless suggest that by presenting certain antigens from normal tissues or from future tissue grafts to young *T* cells in the thymus we will eventually be able to prevent unwanted immune reactions efficiently.

FURTHER READING

TOLERANCE IN T-CELL-RECEPTOR TRANSGENIC MICE INVOLVES DELETION OF NONMATURE CD4+8+ THYMOCYTES. Pawel Kisielow et al. in *Nature*, Vol. 333, No. 6175, pages 742–746; June 23, 1988.

THYMIC MAJOR HISTOCOMPATIBILITY COMPLEX ANTIGENS AND THE ALPHA-BETA T-CELL RECEPTOR DETERMINE THE CD4/CD8 PHENOTYPE OF T CELLS. Hung Sia Teh et al. in *Nature*, Vol. 335, No. 6187, pages 229–233; September 15, 1988.

DEVELOPMENTAL BIOLOGY OF T CELLS IN T CELL-RECEPTOR TRANSGENIC MICE. Harald von Boehmer in *Annual Review of Immunology 1990*, Vol. 8; pages 531–556.

Natural Selection and Darwin's Finches

The finches of the Galápagos—the classic example of how natural selection works over millions of years—have now been observed to evolve in real time. A single drought can change a population

by Peter R. Grant

Every year vast numbers of eggs are produced by creatures as small as parasitic nematode worms and as large as salmon and cod. Orchids may disperse a thousand seeds. Other organisms, such as tortoises and coconuts, reproduce much more slowly than this. Yet one demographic feature is common to all: when a population remains at about the same size for a long time, each parent, on average, replaces itself with just one breeding offspring. That ecological simplicity belies a subtle evolutionary complexity. Although the population replaces itself, some parents leave more offspring than others, and this imbalance provides the condition for evolution to occur by natural selection.

Natural selection is differential success. A population of sexually reproducing organisms comprises many different individuals: some are larger, thicker, greener or hairier than others. When some organisms survive or reproduce better than others because they are larger or smaller, or because they are more or less hairy, natural selection occurs.

PETER R. GRANT is the Class of 1877 Professor of Zoology at Princeton University, where he is chairman of the department of ecology and evolutionary biology. He first visited the Galápagos Islands in 1973 and has returned almost every year since then to pursue long-term and detailed field studies of Darwin's Finches on two islands. He is author of *Ecology and Evolution of Darwin's Finches* and co-author with his wife, B. Rosemary Grant, of *Evolutionary Dynamics of a Natural Population: The Large Cactus Finch of the Galápagos.* Grant is a fellow of the Royal Society and was a Guggenheim Fellow in 1985-86. He received his Ph.D. from the University of British Columbia in 1964 and taught at McGill University and the University of Michigan before joining the faculty of Princeton in 1985.

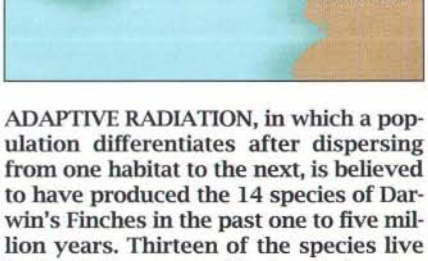
Charles Darwin devised the concept of natural selection while attempting to explain the evolution of organic diversity. His theory has been elaborated, extended and corrected; it has been founded in physical evidence of which he was unaware, such as DNA and the genes it encodes. The evolutionary mechanism is key to any general understanding of how the world came to be the way it is. Yet it is remarkable that 132 years after the publication of his masterpiece, *On the Origin of Species by Means of Natural Selection,* natural selection is still not widely understood.

There are three reasons for this incomprehension. Natural selection has been discussed in misleading terms, such as "fitness," which are charged with unfortunate meanings. Also, popularizers have confused natural selection with related concepts, such as inheritance. Finally, Darwin himself mistakenly assumed that natural selection necessarily proceeds at a snail's pace and that it therefore cannot be observed but merely deduced. He said as much in a famous passage in *Origin of Species:*

> It may be said that natural selection is daily and hourly scrutinising, throughout the world, every variation, even the slightest; rejecting that which is bad, preserving and adding up all that is good; silently and insensibly working, whenever and wherever opportunity offers, at the improvement of each organic being in relation to its organic and inorganic conditions of life. We see nothing of these slow changes in progress, until the hand of time has marked the long lapses of ages, and then so imperfect is our view into long past geological ages, that we only see that the forms of life are now different from what they formerly were.

Darwin argued that new species are formed when persistent selection over many generations changes a population so much that its members will no longer breed with individuals from a related population. But if natural selection indeed occurs solely on a historical scale, the study of evolution would be seriously impeded. The subject would not be amenable to scientific observation and experimentation.

Fortunately, this is not the case. John A. Endler of the University of California at Santa Barbara has recently compiled a list of more than 100 studies that have demonstrated natural selection in action. Some of the most easily interpreted cases have been witnessed in environments altered by human activities. Certain grasses, for example, have become tolerant to the high concentrations of lead in mine tailings. The most common and dangerous cases occur



ADAPTIVE RADIATION, in which a population differentiates after dispersing from one habitat to the next, is believed to have produced the 14 species of Darwin's Finches in the past one to five million years. Thirteen of the species live in the Galápagos Archipelago (*above*).

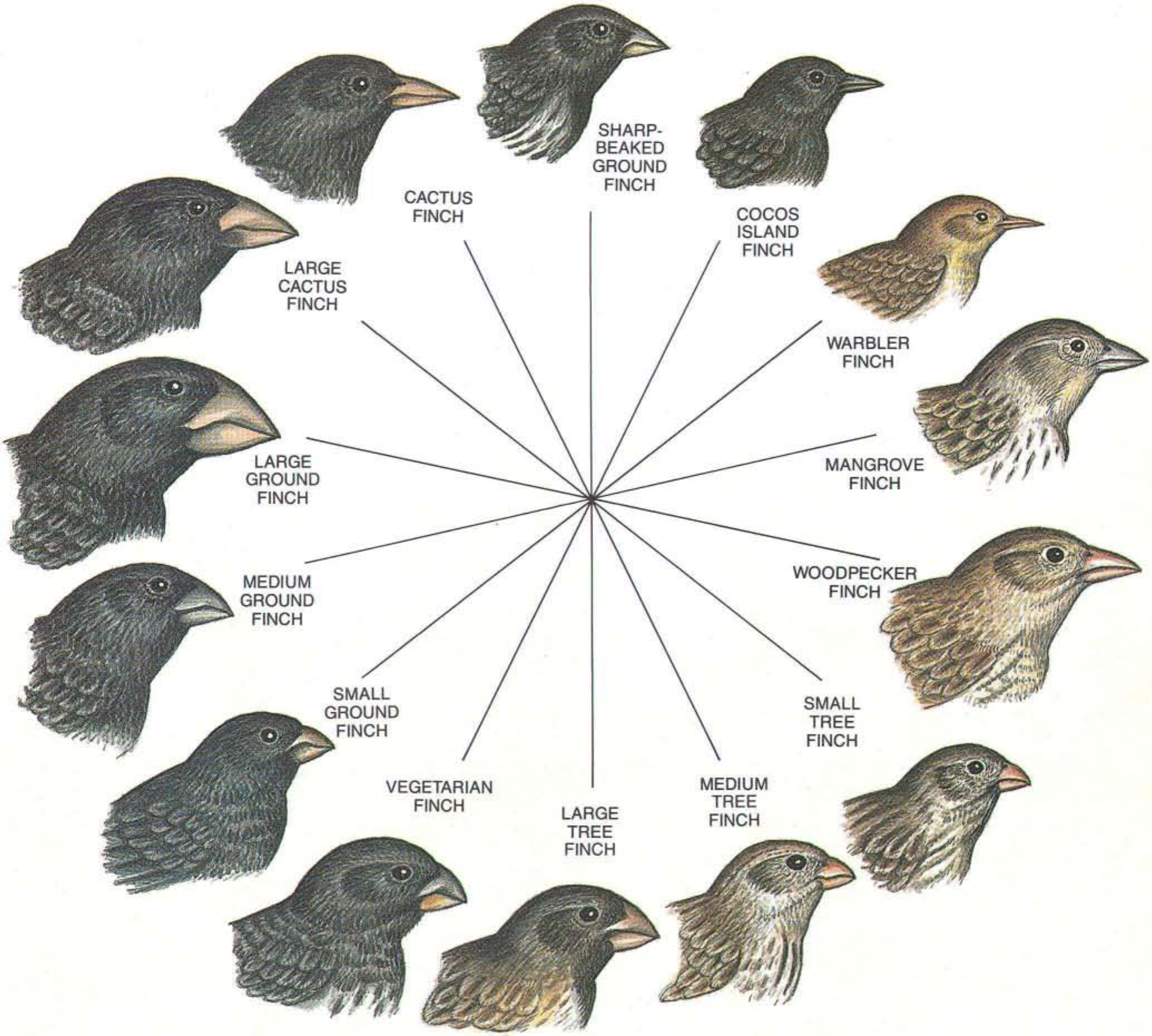
when an antibiotic fails to kill all the bacteria infesting a patient because a few of them are naturally resistant to it. In evolutionary terms, the treatment has selected for resistance to the drug. If the surviving microorganisms can pass their resistance on to their daughter cells, a new strain evolves.

Studies of natural selection in natural environments have broader implications, for they help us understand more directly the evolution of organic diversity over the long history of the earth, the problem Darwin tried to solve. The finches named after him provide an unusually clear illustration.

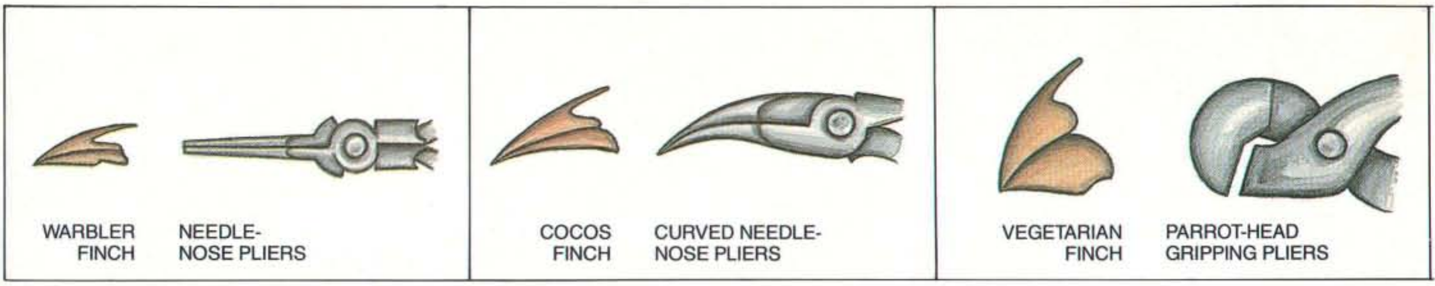
Thirteen species of Darwin's Finches live on the Galápagos Islands, having evolved from a common ancestor, it is believed, in the past one to five million years. The birds are darkly colored and of similar bodily proportions, but they vary in length from about three to six inches (seven to 12 centimeters)—the range between a warbler and a rather fat sparrow—and in the shape of their bills, which reflects their different diets. The common names label their niches and affinities: tree finches, ground finches, cactus finches, a warbler finch, a vegetarian finch, a woodpecker finch and a mangrove finch.

The finches provide a prime example of adaptive radiation, as described in these pages nearly 40 years ago [see "Darwin's Finches," by David Lack; Scientific American, April 1953]. Lack noted that the only other group of birds that display a similar pattern, the sicklebills (honeycreeper finches) of Hawaii, also live in an archipelago, and he suggested that many or even most species differentiated in some kind of physical isolation. "What is unique about the Galápagos and Hawaii," he wrote, "is that the birds' evolution there occurred so recently that we can still see the evidence of the differentiations." The evidence is in fact more than recent, it is ongoing: I have seen the finches evolve in response to climatic changes during the past dozen years. These changes can be dramatic. In some years the islands are drenched by rains precipitated by El Niño events; in other years they are parched by drought.

In 1973 I began studying the finches living on Daphne Major, an islet that covers only about 100 acres. This area was small enough to limit the two resident populations—the medium ground finch, *Geospiza fortis*, and the cactus finch, *G. scandens*—to a number that could be studied exhaustively. I have



Beaks as Tools



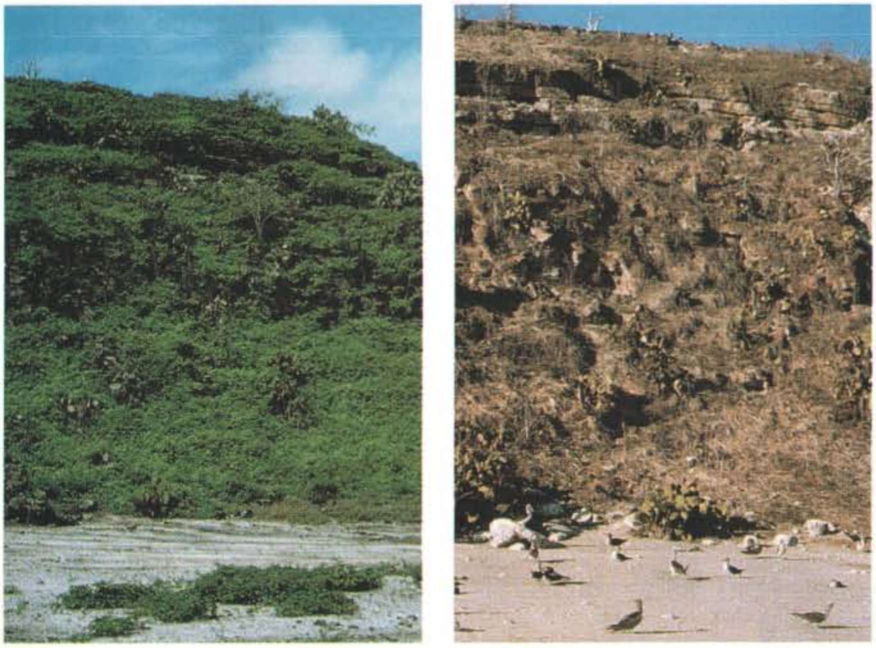
been aided in this endeavor by my wife, Rosemary, and, each year, by two graduate students or other assistants.

We captured the birds in mist nets, so called because their fine filaments are scarcely visible against a dark background. We measured the birds and banded their legs with a numbered metal band and three plastic bands, which allowed us to identify each bird from a distance. Each triplet of colors was coded to correspond to the number on the metal band. By 1977 we had banded more than half of the island's birds, a proportion that passed 90 percent in 1980 and has remained near 100 percent ever since. Thus, from an early stage we were in a position to detect natural selection, if it occurred.

In 1977 it did. In that year Daphne Major had a drought: less than an inch (25 millimeters) of rain fell in the normal wet season. Deciduous plants produced few leaves, and caterpillars were scarce. Some pairs of cactus finches bred, but within three months all their offspring had vanished. Medium ground finches did not even breed. There was a long, dry and unproductive period from the middle of 1976 to early January 1978, when the rains resumed.

During the 18 months, many birds disappeared. Medium ground finches were the hardest hit—only 15 percent remained. Moreover, the winnowing process selected for large size in both species. Although birds of all sizes were reduced in number, the smaller ones were reduced the most. In addition, a conspicuous feature of the survivors was their large beak size.

The missing birds had either died or emigrated. Although the emigration of a few individuals cannot be ruled out, there are two reasons to believe that death was the major cause of the disappearance. First, none of the birds that disappeared in 1976 and 1977 reappeared in 1978. Second, a sample of 38 birds found dead on the island had measurements much closer to the failures than to the successes.



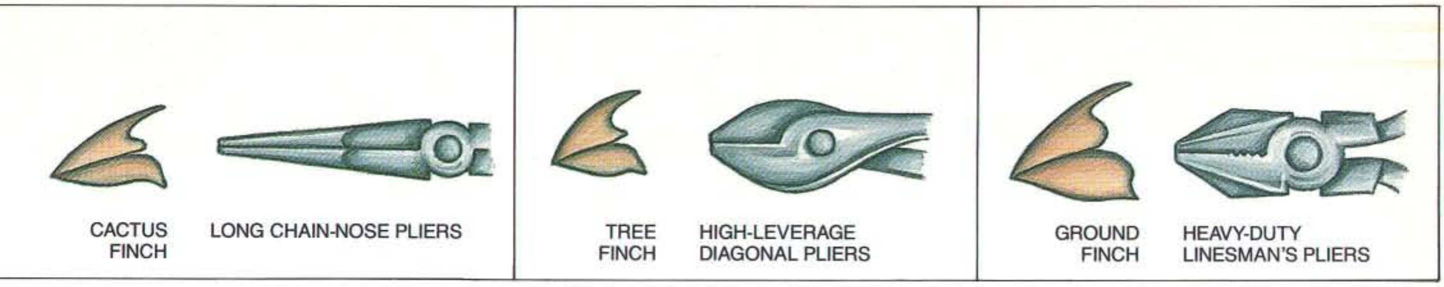
FAT AND LEAN YEARS are evident in these photographs of a craterlet on Daphne Major, a small island in the Galápagos, taken in April 1987 (*left*) and in March 1989 (*right*). The changing weather alters the mix of foods, affecting different populations in different ways. The blue-footed boobies (*right*), for example, live in the craterlet only during times of drought.

The pattern was repeated in 1982, when there was little rain, scarcely any breeding and heavy mortality, particularly among the small birds. The recurrence of size-selective mortality under similar conditions suggests a common environmental cause. The major environmental consequence of drought (besides the lack of water) is the decline in the food supply. For the ground finch, this means seeds.

During normal wet seasons, many grasses and herbs produce an abundance of small seeds, and a few other plant species produce a much smaller number of large seeds. As the finches deplete the supply of small seeds, they turn increasingly to the large seeds. That is when larger birds have the advantage: their bigger, deeper beaks equip them better to crack open the large seeds and get to the kernels. This advantage would tell in the drought years, when the birds' dependence on the crop of large seeds was more pronounced and prolonged than in other years.

The hypothesis for size-selective mortality could be tested in a controlled experiment by altering the composition and abundance of the food supply for one group of birds but not for another. Such experiments are not feasible in the Galápagos National Park but can be done with other bird species elsewhere. This untested hypothesis is plausible, but it is not the only explanation. Large birds may have survived well because their body size allowed them to dominate other finches in social interactions at restricted sources of food or moisture.

Since body size correlates with beak depth, it is not immediately apparent whether one or the other, or both, played a role in survival. A statistical analysis is needed to isolate the association that each factor, considered separately, has with survival. We used partial regression and found that body



size and beak depth each correlated positively—and about equally—with survival. Beak length, on the other hand, did not. Thus, a combination of morphological, behavioral and possibly physiological factors helped to determine which birds survived and which ones succumbed to environmental stress.

Interestingly, Darwin may have witnessed a similar instance of natural selection without noticing it. He estimated that as many as four fifths of the birds in southern England perished during the severe winter of 1854–55. Selection may have been at work, for mortality was similar to what we observed among the medium ground finches in 1977.

I have thus far referred to survival rather than fitness in order to avoid a misunderstanding created more than a century ago by Herbert Spencer. Spencer erroneously equated natural selection with "the survival of the fittest," a catch phrase he coined to popularize Darwin's work. The problem is one of circular reasoning: when the fittest are manifested as such only by surviving, the phrase reduces to the survival of the survivors. Nevertheless, survival of the fittest—or better, the higher frequency of survival among the fittest—does convey part of the essence of natural selection, provided two points are understood. First, some individuals are more fit than others by virtue of their particular traits; second, fitness is ultimately judged by the number of offspring an individual contributes to the next generation.

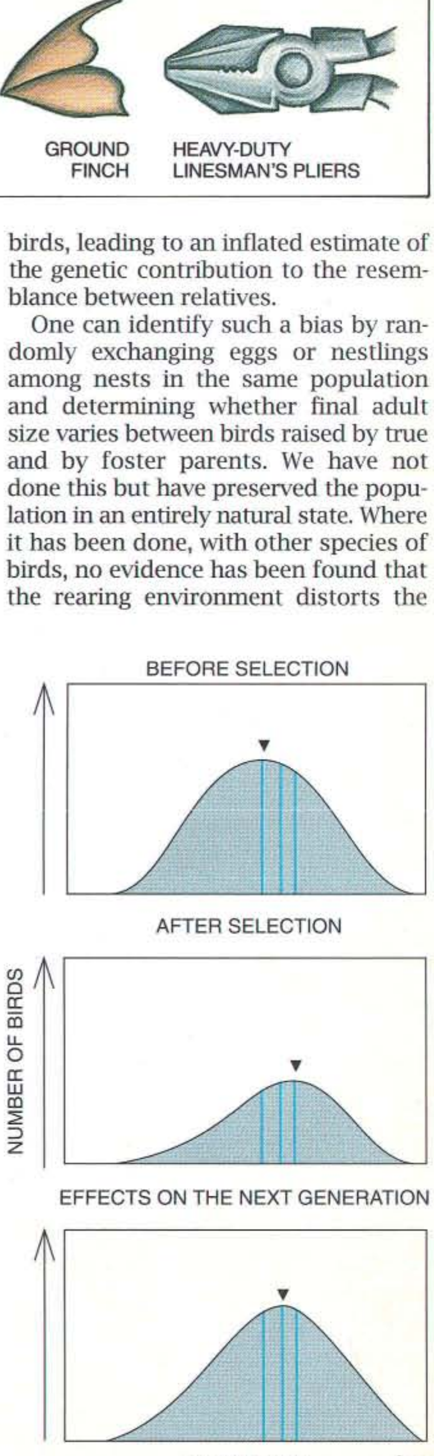
It is equally essential to avoid confusing selection with genetic variation, that is, with the genes that control variation in the traits on which selection operates. As the British geneticist J.B.S. Haldane emphasized, selection has no effects on the next generation unless it influences traits that are to some degree under genetic control and thus heritable. If the traits are heritable, however, then selection causes a small evolutionary change in the population. Therefore, an important question to ask is whether beak depth and body size in the medium ground finch population are heritable.

The heritability of a trait is a measure of the degree to which the trait varies in a population as a result of the additive effect of genes. Thus, large birds may be large in part because of the particular set of genes they inherit from their parents and in part because of the favorable conditions they experience in early life while growing to their final adult size. Similarly, small birds may be small for a combination of genetic and environmental reasons. The degree to which genes influence body size or beak size can be measured by the average similarity between offspring and their parents. This is accomplished by regressing the average of the offspring measurements on the average of the mother's and father's measurements for as many families as possible, a standard procedure in quantitative genetics. The heritability of the trait is estimated by the slope of the function, which can vary between zero and one.

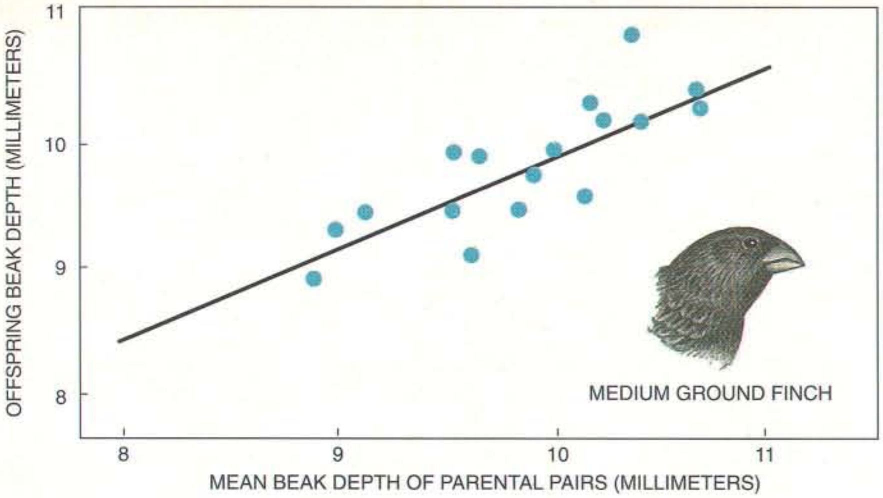
This technique enabled us to estimate the heritability of beak depth in the medium ground finch population at 0.74 [*see top illustration on next page*]. In other words, 74 percent of the variation in beak depth can be attributed to the additive effects of all the relevant genes. The remaining 26 percent is largely attributable to environmental causes. Body size has a somewhat higher heritability, 91 percent. Other morphological traits, including beak length and wing length, have similarly high heritabilities.

Such estimates are subject to the effects of hidden biases, above all the possibility that organisms resemble their parents in part because they grow up in similar environments. Birds might, for example, grow to relatively large adult size in the better territories. If, when seeking their own territories, they outcompete smaller birds for the better territories, they would be able to rear offspring that also reach large adult size. The same self-perpetuating process might work on small birds, leading to an inflated estimate of the genetic contribution to the resemblance between relatives.

One can identify such a bias by randomly exchanging eggs or nestlings among nests in the same population and determining whether final adult size varies between birds raised by true and by foster parents. We have not done this but have preserved the population in an entirely natural state. Where it has been done, with other species of birds, no evidence has been found that the rearing environment distorts the



MICROEVOLUTION occurs in three stages: a population with a given distribution of a trait, such as beak depth (*top*), undergoes selection for that trait (*middle*) and then bequeaths some fraction of the selection's effect to the next generation (*bottom*). The difference between the second and third stages depends on the heritability of the trait.



HERITABILITY OF BEAK DEPTH is estimated by finding the slope of the line that graphs the measurements of each pair of parents against those of their offspring.

estimation of heritability. Our check was different: we compared birds in food-rich and food-poor territories and looked for a tendency for offspring to breed in the kind of territory in which they were raised. We found no such tendency.

Other small errors may also be present, but there is little doubt that body size and beak depth are highly heritable in this population. Therefore, effects of selection on these two traits are passed on genetically to the next generation, causing evolutionary change in the population.

The change is quantified by selection and heritability factors, the product of which should account for the difference between the mean measurement of a trait before selection occurs and the mean in the next generation. The difference, which is normally expressed in standard deviations, is called the evolutionary response to selection.

If selection occurs but the trait has a heritability of zero, then the offspring should not differ from the parental generation before it underwent selection. In Haldane's words, selection will have been ineffective. On the other hand, if all variation in the trait is genetic and the heritability is one, then there is no discounting: the offspring will have a mean identical to that of their parents. These are the extremes; most cases fall in between.

Evolutionary response to selection becomes more complicated when more than one trait is influenced by selection at the same time, for then the genetic variation of each trait interacts with that of the others. Such genetic covariance affects the response. We can minimize these complications by replacing the several traits with an index, which functions as a single synthetic trait. The index accounts for most of the variation among individuals in all dimensions—body size, beak depth and so forth.

Peter T. Boag, now at Queen's University in Kingston, Ontario, adopted this approach while working as my graduate assistant in the late 1970s. He used the first component from what is called a principal components analysis of morphological variation. This synthetic trait, which has the high heritability of 0.75, is best interpreted as a body-size index. It accounts for 64 percent of the variation in the size of the beak, wing, leg and other body parts of the medium ground finches.

Selection on this synthetic trait produced an evolutionary response of 0.36 standard deviation (SD). This accorded well with the predicted value of 0.40 SD, obtained from the measured selection differential and heritability. Thus, a microevolutionary change took place in this population as a result of natural selection. It amounted to an increase in the average beak depth and body size of about 4 percent.

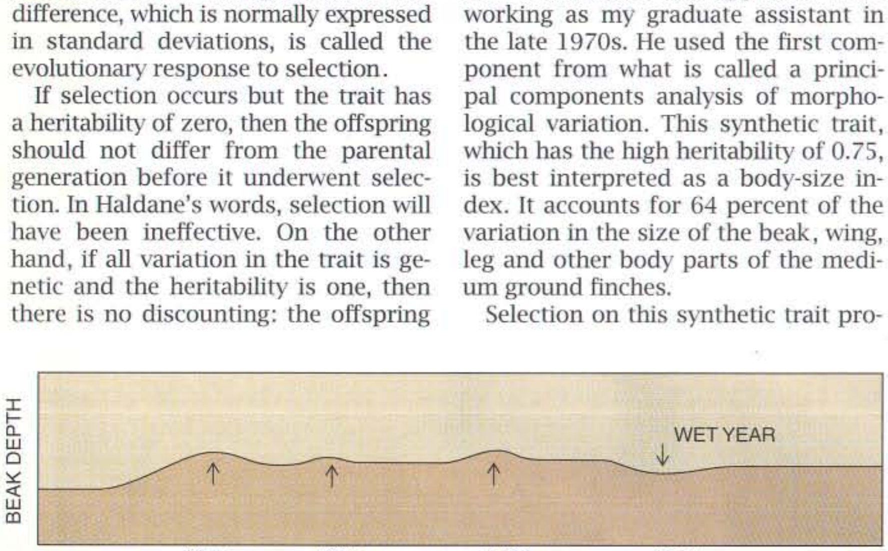
Studies of natural selection as an observable process help us to understand retrospectively processes of evolution that took millennia to unfold. This is particularly true of the pattern of change involved in speciation. In the case of Darwin's Finches, for example, we can extrapolate the observed microevolutionary change to infer the magnitude, causes and circumstances of changes in the formation of one species from another.

Trevor D. Price, now at the University of California at San Diego, and I attempted to do this by taking into account the genetic variation governing morphological traits and the magnitude of the directional selection that occurred in 1977. The two quantities allowed us to estimate the number of such selection events required to transform the medium ground finch, *G. fortis,* into its close relative, the large ground finch, *G. magnirostris,* which is about 50 percent larger.

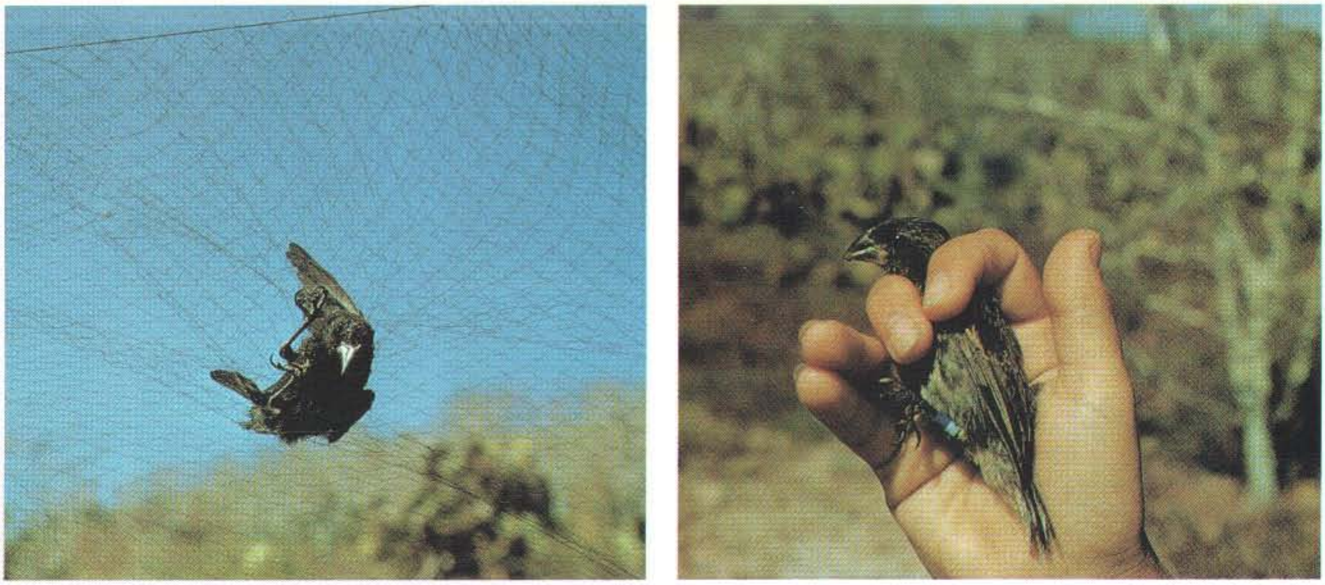
The number is surprisingly small: about 20 selection events would have sufficed. If droughts occur once a decade, on average, repeated directional selection at this rate with no selection in between droughts would transform one species into another within 200 years. Even if the estimate is off by a factor of 10, the 2,000 years required for speciation is still very little time in relation to the hundreds of thousands of years the finches have been in the archipelago.

Far more time is needed to form a species differing from its progenitor in shape rather than size, for then selection must work in opposite directions on different traits, in the face of positive correlations between them. The transformation of the medium ground finch into the cactus finch, for example, would require a relative increase in beak length but a relative decrease in beak depth and in body mass—a process we estimate would take six times longer than the transformation into the large ground finch.

An alternative to this scheme of speciation occurring on a single island is one involving the colonization of several islands in the archipelago. One species becomes transformed into another through the cumulative effects of se-



OSCILLATING TRAIT, in this case beak depth, reflects the fluctuating selective effects of the weather. Droughts (*arrows*) favor birds having the deeper beaks, which are more effective in cracking large seeds, a critical food when rainfall is scant.



BIRD IN THE BUSH is snagged in a mist net (*left*) and then banded by hand (*right*) as part of the author's long-term project to follow the life histories of all the finches living on two small islands of the Galápagos.

lection, predominantly or solely in one direction, on not one but a series of islands. That suggestion is plausible because, as our field studies have shown, each island has a distinctive constellation of types of food for the finches, so in dispersing from one island to another they encounter a different food supply.

In each case, selection will drive the traits of newly established populations fairly rapidly toward the optimal attainable form. Stabilizing selection will then hold the population near that optimum until the environment changes, causing an alteration in diets, perhaps as a result of a rise or decline in the number of competing organisms.

Most species observed in nature appear to have attained stable forms and behaviors. One might conclude, then, that Darwin's Finches on Daphne Major constitute an exception, in that the population is currently heading in the direction of becoming a larger species. This hunch may be right, but I doubt it: other factors are also at play.

Effects of the droughts of 1977 and 1982 were approximately offset by selection in the opposite direction—toward smaller body size—in 1984–85 [*see bottom illustration on opposite page*]. A relative scarcity of large seeds, together with an ample supply of small ones, favored small finches. Because the food supply on this island changes in composition and size from year to year, the optimal beak form for a finch is shifting in position, and the population, subjected to natural selection, is oscillating back and forth with every shift. Whether or not there is a net directional trend toward larger size, like an arrow through the oscillations, is unclear and could be determined only by a much longer study. Such a trend may come to pass, if human-induced global warming increases the incidence of drought in the Pacific.

We have observed fluctuations of a somewhat different kind in the population of the large cactus finch, *G. conirostris,* on Genovesa, 55 miles to the northeast of Daphne Major. In this case, the foods provided by cactus bushes changed as a result of extremely wet conditions produced by El Niño in 1983. In the next year long-billed birds were at a disadvantage because the food they are best equipped to exploit, cactus flowers and fruits, declined drastically. In 1985, a drought year, the birds had little to eat except the arthropods living under the bark of trees and in the tough pads of cactus bushes. Under these changed circumstances, the finches with strong, deep beaks were best equipped to extract the arthropods. As a result of this advantage, they had the highest rate of survival.

Oscillating direction selection may furnish a general model for what happens elsewhere—and not just to populations of birds. Annual variation in environmental conditions is pronounced, as we know from the summers in the U.S. during the past decade. We also know that many populations of animals, from insects to mammals, fluctuate greatly in numbers under the influence of a varying climate. Most of these populations live in the temperate zone, but even the inhabitants of tropical rain forests are not as stable in numbers as was once assumed.

When a population fluctuates, gene frequencies are likely to change as a result of random processes, especially when the population declines to low numbers. The unanswered question is whether, in addition to this process, demographic fluctuations in a wide variety of organisms are accompanied by microevolutionary changes in phenotypic traits as a result of natural selection. My guess is that they often are, but proof will require detailed studies of individually recognizable members of a population. If oscillating selection is indeed widespread and not just a peculiarity experienced by Darwin's Finches and a few other organisms, then the model will constitute a powerful tool to help us achieve Darwin's goal: the explanation of the causes of organic diversity.

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The Origins of the Asteroids

Once regarded as "vermin of the skies," asteroids are now known to offer important clues to the birth of the solar system. They are the remnants of a planet that failed to form

by Richard P. Binzel, M. Antonietta Barucci and Marcello Fulchignoni

On October 29 of this year, the spacecraft *Galileo,* bound for Jupiter, will use its sophisticated sensors—among them a mapping spectrometer, radiometer and photopolarimeter—to investigate a 12-kilometer-wide body that may be shaped like a potato. The target, 951 Gaspra, is one of more than several thousand asteroids known to exist between Mars and Jupiter. Once referred to as uninteresting "vermin of the skies," asteroids store a rich variety of information that is proving to be of scientific and pragmatic interest.

Astronomers used to believe that these small worlds were the debris of a shattered planet. Actually, asteroids are remnants of a planet that failed to form. As such, they offer significant evidence of the nature of the poorly understood process that creates planets. They also provide clues to conditions in the early solar system.

Moreover, a number of asteroids reside in the inner solar system, within the orbit of Mars, and many of their orbits intersect that of the earth. Evidence of past catastrophic impacts pervades the geologic record, indicating that collisions can strike with a force exceeding that of a nuclear warhead.

RICHARD P. BINZEL, M. ANTONIETTA BARUCCI and MARCELLO FULCHIGNONI have asteroids bearing their names: 2873, 3485 and 3486, respectively. Binzel, an associate professor of earth, atmospheric and planetary science at the Massachusetts Institute of Technology, received a Presidential Young Investigator award in 1990. He described Pluto in the June 1990 issue of SCIENTIFIC AMERICAN. Barucci, an astronomer at the Paris Observatory, received her doctorate from the University of Rome. She is involved with the asteroid encounters of the Cassini mission to Saturn. Fulchignoni began his research in space science during the Apollo program, analyzing lunar samples. A professor of physics of the solar system at the University of Rome, he is currently editor in chief of the international journal *Annales Geophysicae.*

Unlike planets and comets, which have been known since antiquity, asteroids are a relatively recent discovery. They were found as the consequence of an inquiry into the spacing of the planets, a phenomenon that mystified astronomers of the 17th and 18th centuries. In 1766 the German astronomer Johann D. Titius calculated that a planet should exist between Mars and Jupiter, about 2.8 astronomical units (AUs) from the sun (one AU is defined as the earth's average orbital distance, about 150 million kilometers). Johann E. Bode of the Berlin Observatory later popularized the calculations, which became known as Bode's Law.

The search for the "missing planet" began in earnest at the turn of the 19th century, when the Hungarian baron Franz X. von Zach organized a group of astronomers who called themselves the celestial police. On January 1, 1801, the search apparently ended: Giuseppe Piazzi of Palermo discovered an object and named it Ceres, after the tutelary goddess of Sicily.

Although the discovery delighted astronomers, Ceres posed a puzzle. Observed through a telescope, it showed no disk, implying that it was substantially smaller than anticipated. Astronomers had expected a more massive object. The first clue in the solution to the "missing mass" problem came in 1802, when Heinrich W. M. Olbers found a second small planet, later named Pallas. By 1807 observers discovered the third and fourth minor planets, Juno and Vesta. Olbers suggested that these bodies were fragments of a larger planet that ruptured. Sir William Herschel, who discovered Uranus, proposed that these minor planets be called asteroids, Greek for "starlike," a term justified by their telescopic appearance.

Observations over the past two centuries have identified a total of about 18,000 asteroids. Astronomers have determined the precise orbits of about 5,000 of them. Each of these asteroids has a permanent catalogue identification consisting of a number that denotes its order of entry, which is usually followed by a name proposed by the observer. For instance, "3 Juno" formally identifies the third asteroid discovered. Only preliminary data characterize the orbits of the other 13,000; instead of a catalogue number, each is marked by its year of discovery and two letters indicating the date of first observation.

Most asteroids orbit within a confined area between Mars and Jupiter—called the main asteroid belt—at an inclination of about 10 degrees with respect to the plane of the solar system. Their average distances from the sun (referred to as the semimajor axes because the orbits trace ellipses) range between 2.1 and 3.3 AUs. Ceres, Pallas and Vesta hold about one half of the total mass of the asteroid belt, equal to about 0.0005 the mass of the earth. Their diameters are 933, 523 and 501 kilometers, respectively. About 1,000 asteroids are larger than 30 kilometers across, and of these, more than 200 asteroids are larger than 100 kilometers. Not all the asteroids smaller than 30 kilometers have been discovered, but calculations indicate there are about one million whose diameters measure one kilometer or more.

Such a vast number conjures images from popular films that show spacecraft weaving through fields of crashing boulders. The volume of space in the main belt is so large, however, that asteroids usually remain several million kilometers apart. Collisions are infrequent; significant events occur only over geologic time scales.

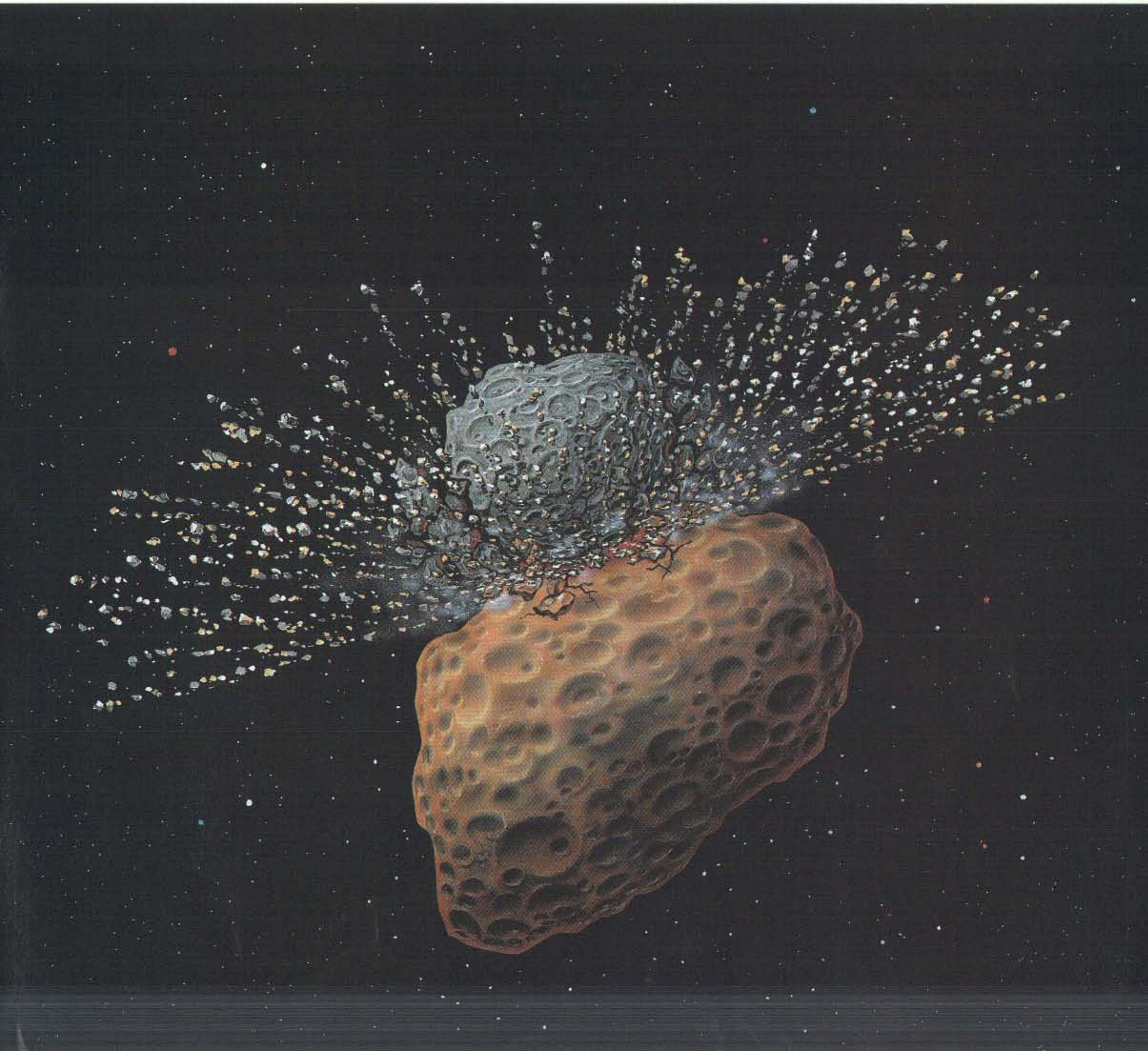
Gravitational effects from Jupiter

ASTEROID COLLISION, an event that occurs frequently over geologic time scales, largely determines an asteroid's size, shape and rotation rate.

dominate the structure of the asteroid belt. Such effects first became evident in 1867, when the American astronomer Daniel Kirkwood found breaks in the uniformity of the asteroid belt. These depletions, called Kirkwood gaps, occur in regions where the orbital period of a body would be some exact integer ratio of Jupiter's orbital period. For instance, an object 2.5 AUs from the sun is said to be at the 3:1 "resonance"; that is, the body would complete exactly three revolutions for every one that Jupiter completes. Some resonances tend to isolate asteroids into groupings, as is the case for assemblies known as Hungarias, Phocaeas and Cybeles. Other resonances show concentrations. A group called the Hildas resides in the 3:2 resonance, and 279 Thule is apparently constrained in a low-eccentricity orbit near the 4:3 resonance.

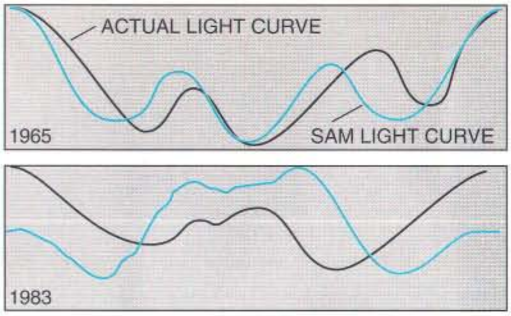
The resonances do not just define the structure of the asteroid belt. In all likelihood, they prevented the formation of a planet between Mars and Jupiter. The inner planets formed when swarms of planetesimals a few kilometers in size collided at velocities low enough to permit the bodies to grow larger by accretion. Numerous resonances from the rapidly growing and massive planet Jupiter probably permeated the region between two and four AUs. These resonances may have pumped up the orbital eccentricities of the planetesimals there, accelerating the objects to velocities so high that successful accretion on a planetary scale was impossible. Today the asteroids remain in an environment dominated by collisions, encountering one another at about five kilometers per second.

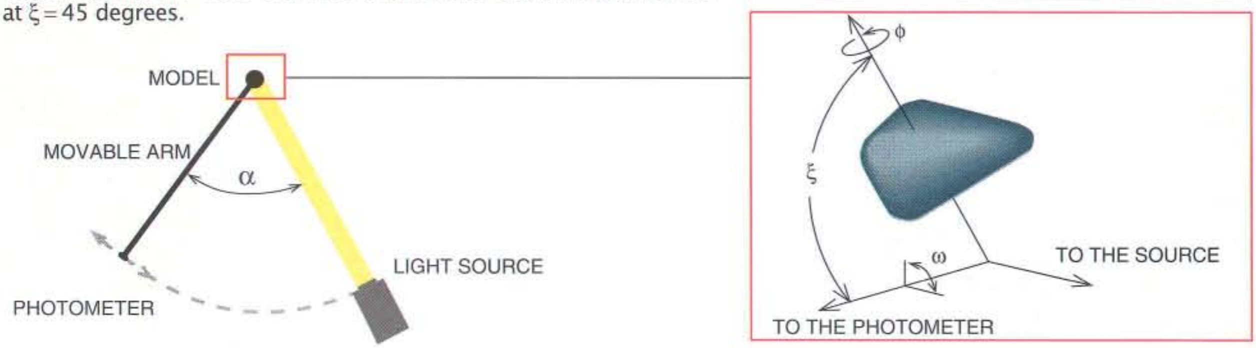
Increasing eccentricities may have also led to the collisional pulverization of some asteroids. In addition, collisions with planets or interactions with their gravitational fields (especially that of Jupiter) can effectively remove or scatter wayward bodies from the solar system. These events may have cleared the asteroid zone of most of its original mass, leaving behind the remnants observed today.



Modeling Asteroid Shapes

One way to determine the shapes of asteroids is to generate synthetic light curves from models. A simple instrument (*below*), called the System for Asteroid Models (SAM), shines light on an object (here, an egg-shaped cone that resembles the asteroid 29 Amphitrite). A photometer measures the reflected light from various angles (α). The orientation of the object can also be changed along three angles (ξ, ϕ, ω). Synthetic light curves so generated closely match the actual ones from Amphitrite (*right*). The 1965 measurement corresponds to an "equator-on" view of the model (ξ = 90 degrees), and the 1983 curve resembles that of the model inclined at ξ = 45 degrees.





Some clusters of main-belt asteroids seem to share specific orbital distances, eccentricities and inclinations. In 1918 the Japanese astronomer Kiyotsugu Hirayama called these clusters families. He identified and named a number of them, including Themis, Eos, Koronis and Flora. Since then, astronomers have used cluster analysis techniques to identify as many as 10 to 100 different families.

Hirayama proposed that families result from the disruption of large parent bodies. If so, the fragments would provide a view of the interiors of the precursor asteroids. The size distribution of family members provides information on the outcomes of collisions. As a result, researchers can use these families to deduce information about how the asteroid belt evolved through collisions since its formation.

Not all asteroids are found in the main belt. An especially interesting group, called the Trojans, resides at the 1 : 1 resonance. These asteroids have the same heliocentric distance and orbital period as Jupiter does. Trojans orbit in two stable regions near equilibrium positions, known as Lagrange points, that lie in the orbital plane about 60 degrees east and west of Jupiter.

Only one object catalogued as an asteroid resides beyond Saturn, about 10 AUs away. Charles T. Kowal of the Space Telescope Science Institute discovered this body, named 2060 Chiron, in 1977. About 200 kilometers wide, Chiron remains an average of 13.7 AUs away from the sun. Its eccentric orbit sometimes carries the object inside the orbit of Saturn. Chiron's unusual and unstable orbit (because of interactions with Saturn) and irregular variations in brightness have recently led most researchers to suspect that the object is a comet. In 1989 Karen J. Meech of the University of Hawaii and Michael J. Belton of the National Optical Astronomy Observatory detected the first definitive cometary activity: a dusty coma around Chiron. Evidence of cometary gas emission came earlier this year, when Schelte J. Bus and his colleagues at the Lowell Observatory detected the spectral signature of cyanogen radicals, which are known to exist in comas. Chiron will most likely be officially designated a comet soon.

Early this year astronomers found another asteroidlike body with a far-ranging orbit. The preliminary orbit for this object, 1991 DA, carries it from near Mars at 1.5 AUs to beyond Uranus at 19 AUs. Physical observations have so far not yielded any definitive conclusion about any possible cometary nature of the object.

Three populations of asteroids reside within the inner solar system. One class, the Atens, has orbits that keep them consistently close to the sun. The semimajor axes of the Aten orbits are less than one AU. A second group, known as Apollo asteroids, has orbital semimajor axes beyond the earth. Some Atens and Apollos orbit so eccentrically that they cross the earth's orbit. A third class is called the Amors. These asteroids travel around the sun between the orbits of Mars and the earth and often cross the path of Mars. Collectively, Atens, Apollos and Amors constitute the near-earth asteroids.

Astronomers think that some source must resupply the near-earth population visible today. Asteroids in the inner solar system live only about 10 million to 100 million years—far shorter than the 4.5-billion-year age of the solar system. Within this lifetime, they disappear, either because of collisions with the inner planets or near misses, which result in their gravitational ejection from the solar system.

Extinct cometary nuclei may be one source of resupply. Comets that exhaust their stores of volatile ices, which form the distinctive comas and tails, may be indistinguishable from asteroids. Several near-earth asteroids have orbits that resemble those of known, short-period comets. Other evidence comes from observations made by Fred Whipple of the Harvard-Smithsonian Center for Astrophysics. He has shown that the near-earth asteroid 3200 Phaëthon follows the orbit of the small bodies that produce the Geminid meteor stream. Previously, meteor streams were known to be associated only with comets. Although comets may evolve into asteroids, this process by itself probably could not account for the entire population.

Workers suspect that the main belt may be supplying the remaining near-earth asteroids, perhaps accounting for as much as 80 percent of them. A description of the delivery mechanism has until recently proved elusive. The solution hinges on findings by Jack L. Wisdom of the Massachusetts Institute of Technology. Some orbits, such as those near the 3:1 resonance, can undergo "chaotic motion." Such motion may lead an asteroid to cross the path of Mars. Studies by George W. Wetherill of the Carnegie Institution have shown that gravitational interactions with Mars further aid the delivery of asteroids to the vicinity of the earth.

Because some asteroids follow paths that intersect the earth's orbit, they represent a threat of collision. Asteroids have struck the earth many times in the past, and the consequences of a large impact are sobering: one such collision may have initiated the mass extinctions 65 million years ago. Smaller impacts, occurring about once every century, release an amount of energy equivalent to that from a single nuclear warhead. The last known event took place on June 30, 1908, near the Siberian Tunguska River, and there have been several close encounters since. For instance, this past January observers discovered the asteroid 1991 BA just hours before it passed within 0.0011 AU—less than half the distance from the earth to the moon.

Other small bodies in the solar system may be asteroids. Phobos and Deimos, the two satellites of Mars, the eight outer moons of Jupiter and the Saturnian satellite Phoebe appear to be captured asteroids.

Although cataloguing bodies and defining orbits occupied the first 150 years of asteroid work, systematic studies of their physical properties began only in the 1950s. Because asteroids display no visible disk, observers must infer physical characteristics from the intensities and spectral properties of the reflected sunlight. Gerard P. Kuiper of the University of Chicago and his students, most notably Tom Gehrels of the University of Arizona, pioneered such studies.

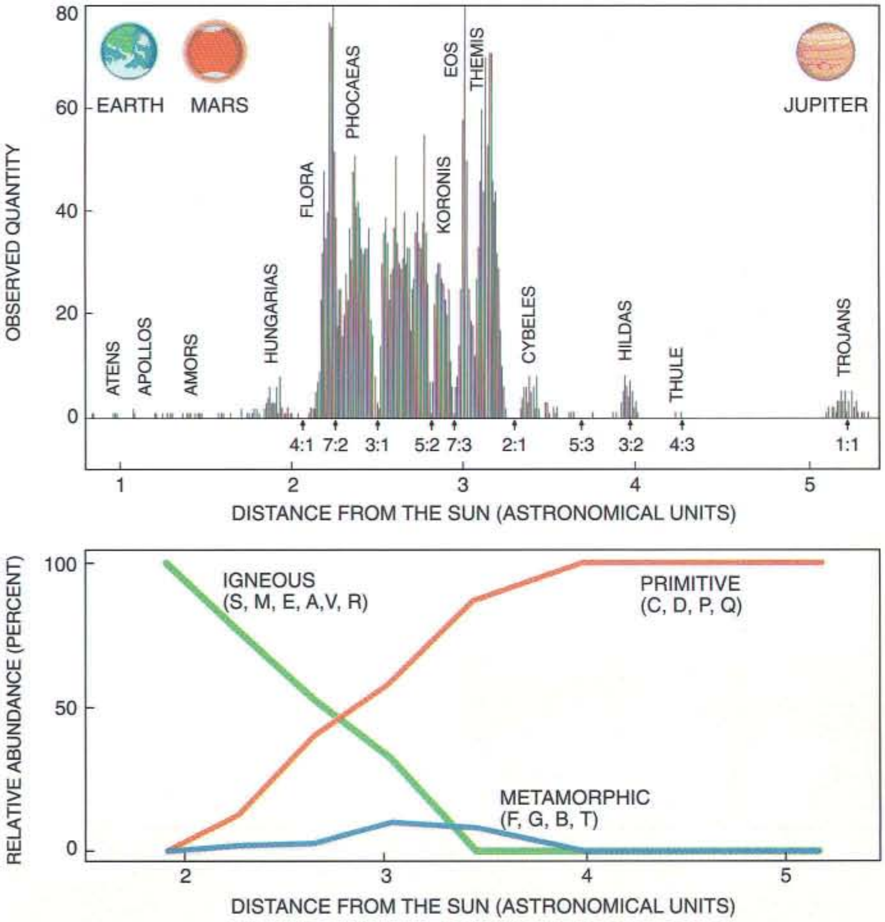
The first physical characteristic noted by astronomers was that most asteroids do not maintain a constant brightness. Short-term variations result from the rotation of an asteroid's irregular shape about the spin axis. The changing cross-sectional area reflects different amounts of sunlight to the earth. Each rotation typically brings two broad and two narrow ends into view, yielding two maxima and two minima in the observed light curve.

The maximum amplitude of the variation gives an indication of the shape. For instance, an elongated body shows a greater variation than does a roughly spherical one. Asteroids typically rotate once every four to 20 hours, and the brightness varies by about 20 percent. The reflectance of some asteroids can change more dramatically; the light intensity from 433 Eros fluctuates by more than a factor of four.

From the accumulated data on the rotation rates, astronomers can infer the kinds of collisions an asteroid has experienced. Each noncatastrophic collision adds rotational angular momentum in a random way. Small asteroids tend to spin quickly. Larger asteroids, which have higher moments of inertia and experience fewer collisions with significantly massive projectiles, spin more slowly.

Curiously, the trend reverses for asteroids larger than about 125 kilometers: spin rates tend to increase with increasing size. The reason may be gravity. Instead of adding angular momentum, a major collision may simply shatter asteroids less than 125 kilometers in size. Larger asteroids, however, have enough mass so that their gravity keeps them intact or causes the shattered fragments to reaccumulate to a mass that spins more rapidly than it did before the collision. Many rapidly rotating and elongated large asteroids are believed to be gravitationally bound "rubble piles"—that is, bodies that are thoroughly shattered in their interiors.

The asteroid's light curve also enables astronomers to determine the orientation of its rotation axis. A highly elongated asteroid will reveal little or no light variation if its spin axis points directly toward the observer in a "pole-on" view. As the asteroid's orbital motion carries it away from this alignment, the amplitude of the light curve increases. The amplitude reaches a maximum when the asteroid provides an "equator-on" view 90 degrees later. One of us

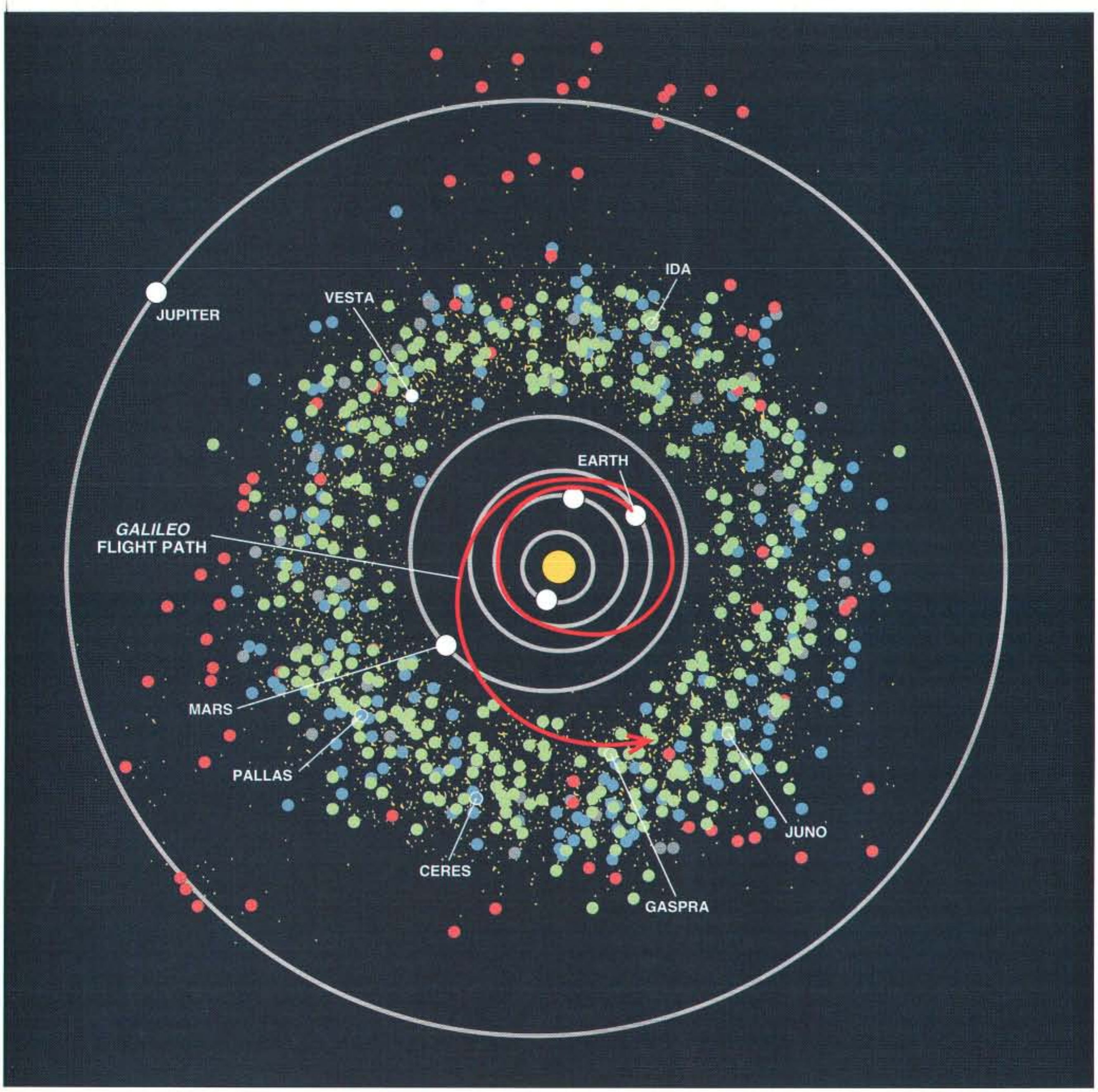


DISTRIBUTION OF ASTEROIDS based on distance from the sun reveals groupings and gaps (*top*). Most asteroids are located in the main belt, between 2.1 and 3.3 AUs from the sun. Effects of resonances, or locations where the orbital period of a body is some exact integer ratio of Jupiter's orbital period, are also visible. Only major groupings and resonances are labeled. Main belt asteroids may be divided into three superclasses: primitive, metamorphic and igneous (*bottom*). The superclasses show a distinct distribution based on heliocentric distance. The letters indicate asteroid types and usually derive from spectral similarities seen in meteorites; however, they serve only as mnemonic devices and do not imply any mineralogical link.

(Barucci) and her colleagues at the Teramo Observatory in Italy used model asteroids in a simple apparatus to generate about 10,000 synthetic light curves for various object shapes. Comparing the synthetic with the measured light curves has greatly aided the understanding of asteroid shapes and surface properties [*see illustration on page 68*].

Although light curves reveal important characteristics of asteroids, such as shape, they do not provide any absolute measure of size. Instead the most widely applied means for estimating size comes from measurements of the thermal radiation asteroids emit. Typically surface temperatures are about 200 kelvins, but that value and the corresponding thermal flux depend on an asteroid's albedo, diameter and distance from the sun. For instance, a low-albedo surface reflects very little solar light; most of the sun's energy is absorbed and reemitted at thermal wavelengths. So for two equidistant asteroids having the same apparent visual brightness, the one showing the greater thermal emission would have the lower albedo and larger diameter.

Because astronomers can quantitatively calculate the incident solar flux on an asteroid, they can use visual and thermal infrared measurements to derive albedos and diameters. The most detailed survey came from the *Infrared Astronomical Satellite* (*IRAS*). Launched in 1983, the satellite provided measurements of nearly 2,000 catalogued and many more uncatalogued asteroids.



ASTEROID BELT girdles the region between Mars and Jupiter. The diagram shows the positions of the asteroids and planets on October 29, 1991—the date *Galileo* will encounter 951 Gaspra, an S-type asteroid. In August 1993 *Galileo* will also visit 243 Ida, another S-type asteroid. (The spacecraft is using the earth's gravity to boost its velocity; hence, the circuitous trajectory.) Asteroids with known spectral properties are colored: S (*green*), C (*blue*), D and P (*red*), and M (*gray*). The primitive C, D and P types dominate the outer part of the belt; the igneous S and M are more common in the inner portion.

The *IRAS* results suggest that the largest asteroids show an albedo distribution different from those of the smallest ones. The fact that many smaller asteroids may be fragments originating in the interiors of larger parent bodies could explain the difference. The *IRAS* discovery of dust bands within the asteroid belt also confirms that collisions occur with relative frequency.

Another method to measure an asteroid's size requires a fortuitous juxtaposition but yields the most accurate results. An asteroid's apparent motion sometimes causes it to pass directly in front of a distant star, occulting it; the shadow of the asteroid then sweeps across the earth's surface. The width of the shadow path measures the length of the asteroid along one dimension. The duration of the star's disappearance multiplied by the calculated shadow velocity yields the other dimension.

Observers have detected more than 40 such stellar occultations. The most successful measurement occurred in 1983, when several hundred amateur astronomers teamed up with professionals to observe the occultation of the bright star 1 Vulpeculae by Pallas. The measured silhouette, when combined with light-curve and previous occultation data, yielded an ellipsoid shape for Pallas with triaxial dimensions of 574 by 526 by 501 kilometers.

One of the most powerful and promising new techniques applied to asteroid studies is radar. Unlike most other astronomical instruments, which passively measure the energy from celestial sources, radar can be used to perform controlled experiments on the target. Observers simply tailor the polarization as well as the time and frequency modulation of the outgoing signal. The return signals contain information on the asteroid's distance, size, shape, spin rate, orientation and surface properties. Major efforts by Steven J. Ostro of the National Aeronautics and Space Administration's Jet Propulsion Laboratory and others have yielded radar echoes from more than 50 near-earth and main-belt asteroids.

Perhaps the most intriguing radar results obtained by Ostro and his colleagues are reconstructed images that reveal the odd shape of 1989 PB (recently catalogued as 4769 Castalia). This near-earth asteroid appears as a bifurcated structure, consisting of two distinct lobes that seem to be in contact. Although cratering could have shaped Castalia, most astronomers believe that the object is a contact binary: two separate bodies collided at low velocity to form the asteroid.

Although many techniques can examine the physical dimensions of asteroids, only spectroscopic measurements can reveal chemical compositions. Because elements and compounds absorb distinct regions of the electromagnetic spectrum, researchers can use spectroscopic data to deduce the chemistry of a body. Compositional information for a large sample of asteroids enables astronomers to determine patterns of formation and thermal evolution as a whole.

As a result of such measurements, researchers recognize many classes of asteroids based on composition. The two broadest groups, first determined in the 1970s, are the C and S classes. The C class consists of low-albedo objects that generally exhibit neutral or flat spectra and have a strong absorption in the ultraviolet. The S class consists of moderate-albedo objects that show a broad absorption band in the blue as well as in the ultraviolet.

Astronomers soon recognized several other classes. A cluster analysis by David J. Tholen of the University of Hawaii, together with surveys, led to a major expansion of the taxonomic system in 1984. The currently recognized classes are designated by the letters S, C, M, D, F, P, G, E, B, T, A, V, Q and R, in order of their observed relative abundances.

Although it seems to be a random alphabet soup, the taxonomy actually reveals a distinct structure in the compositional distribution of asteroids. Building on work by Jonathan C. Gradie of the University of Hawaii and Edward F. Tedesco of the Jet Propulsion Laboratory, Jeffrey F. Bell of the University of Hawaii developed a paradigm for physically understanding the stratification. He grouped the compositional classes into three superclasses: primitive, metamorphic and igneous. Primitive asteroids, which include the C, D and P types, dominate the outer part of the belt. Igneous asteroids, such as S, M and E, are most common in the inner part of the belt. Metamorphic asteroids, consisting of classes F, G, B and T, peak in the central region of the belt.

The distribution pattern suggests some primordial process produced a steep temperature gradient that altered the composition of the asteroids. The primitive asteroids, which are located farthest from the sun, are primarily rich in carbon and water. They represent unaltered remnant material from the formation of the solar system. Metamorphic objects resemble primitive asteroids except that they have fewer volatile compounds and little water. These characteristics suggest that some heating process has transformed some primitive asteroids into metamorphic ones. The igneous asteroids, found closest to the sun, must have been strongly heated. They appear to have formed from a melt and contain complex mineral assemblages.

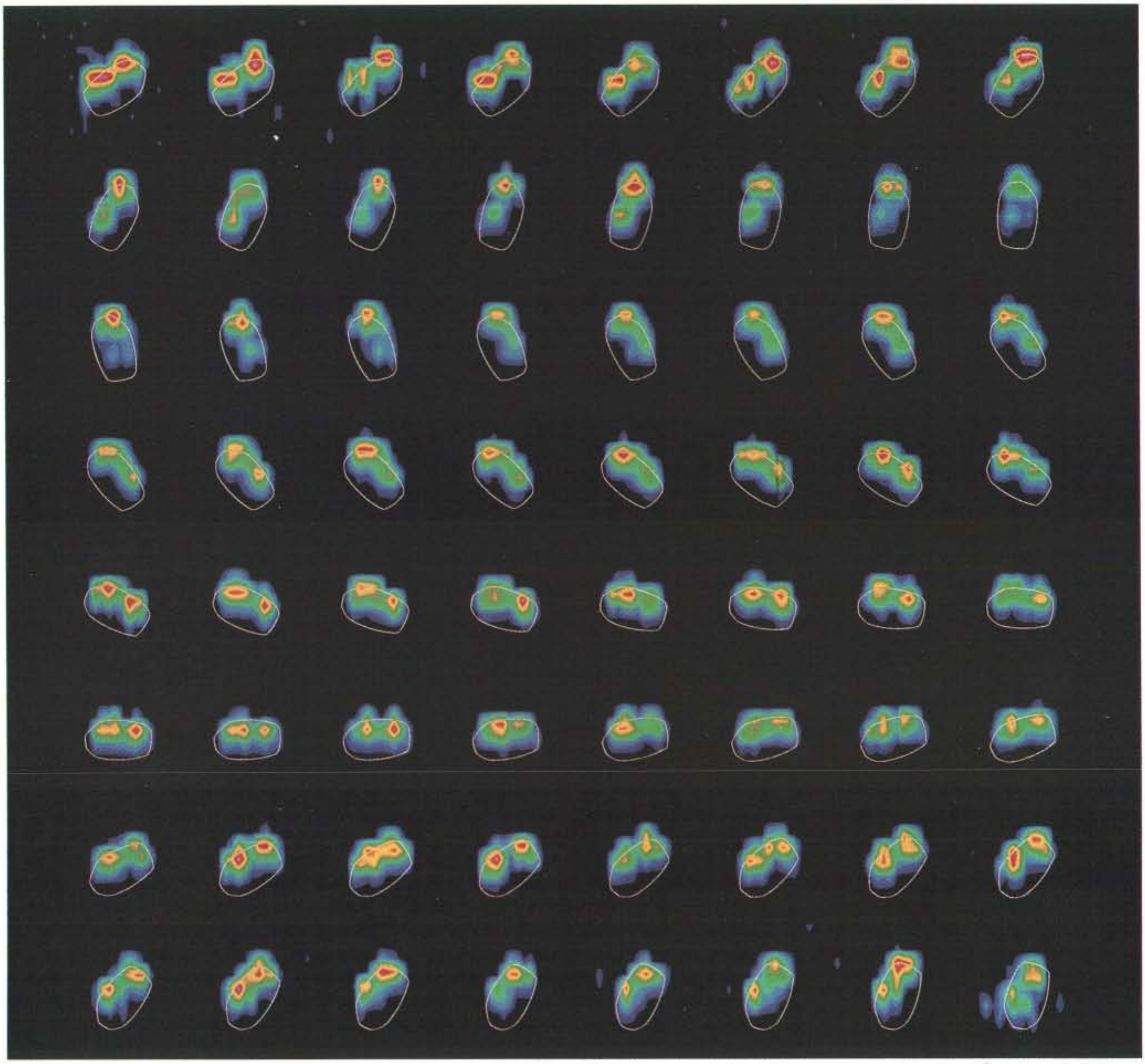
The most likely explanation is heating initiated by a strong solar wind during an early phase in the sun's formation. Such heating could account for the steep distribution gradient of the superclasses with respect to distance from the sun. Some researchers, however, have suggested that the radioactive decay of aluminum 26 served as the heating mechanism. This element could have been injected into the condensing solar system by a nearby supernova. Impacts, too, could have provided some heat to mix and melt the compounds detected on asteroid surfaces.

Mineralogical studies of asteroid spectra do not necessarily have to be remote. Meteorites probably represent samples of material from the asteroid belt. The pieces of the puzzle, however, do not yet fit together neatly. The observed samples of the asteroids and meteorites appear to represent partially mismatched sets. The greatest discrepancy occurs with the most common type of meteorite, the ordinary chondrites. These meteorites, which have relatively primitive compositions, have no spectrally observed analogue in the main belt.

Theorists have proposed that the parent bodies may be the S class asteroids. Such asteroids have the same qualitative mineralogy. Still, their quantitative proportions are difficult to determine. Some researchers think the S types are more metal rich and therefore more closely resemble the stony-iron meteorites—objects that have undergone substantial heating.

One possible answer to the puzzle may be "space weathering." Solar radiation or micrometeoroid impacts could have changed the upper few millimeters of an ordinary chondrite asteroid's surface enough to alter its spectral characteristics. Another solution may come from the recent observations of the near-earth asteroid 1862 Apollo. This asteroid, about two kilometers wide, appears to be spectrally consistent with ordinary chondrites. Cratering impacts may have hurled pieces of 1862 Apollo into earth-crossing orbits. Still, researchers think ordinary chondrites derive from several parent bodies. Perhaps extended surveys will reveal more of this asteroid class (Q).

Discrepancies in the models of collisional evolution remain as well. For example, Vesta's basaltic crust probably resulted from lava flows produced dur-



ASTEROID 1989 PB, recently catalogued as 4769 Castalia, seems to consist of two separate lobes in contact. The sequence of radar images (*left to right, top to bottom*) provides a "pole-on" view of the asteroid's counterclockwise rotation.

ing an acute heating episode in the early solar system. It is difficult to understand how the intense bombardment that completely disrupted many asteroids of similar size could have allowed Vesta to preserve its crust intact.

Partial solutions to such questions may be forthcoming. The Jupiter-bound *Galileo* will fly within 1,600 kilometers of 951 Gaspra on October 29. Ground-based reconnaissance indicates that Gaspra is an irregularly shaped, 12-kilometer-wide, S-type asteroid that rotates once every seven hours. *Galileo* may enable planetary scientists to determine Gaspra's composition, crater density and surface structure.

Preliminary plans are under way for dedicated missions to near-earth asteroids, many of which are more accessible than the moon. The Italian space agency is considering a mission under the name Piazzi for a near-earth asteroid flyby. A new U.S. initiative for a series of inexpensive Discovery missions may also include a rendezvous with a near-earth asteroid.

Still, spacecraft will study relatively few asteroids through the first part of the 21st century. Instead astronomers will continue to rely heavily on observations from the ground and from earth orbit. Planned upgrades to the Arecibo radar facility in Puerto Rico will be able to image hundreds of main-belt asteroids, and a repaired *Hubble Space Telescope* should provide detailed images as well as mineralogical information. The current decade promises to bring a handsome return of information, in time to celebrate January 1, 2001—the bicentennial discovery date of 1 Ceres.

FURTHER READING

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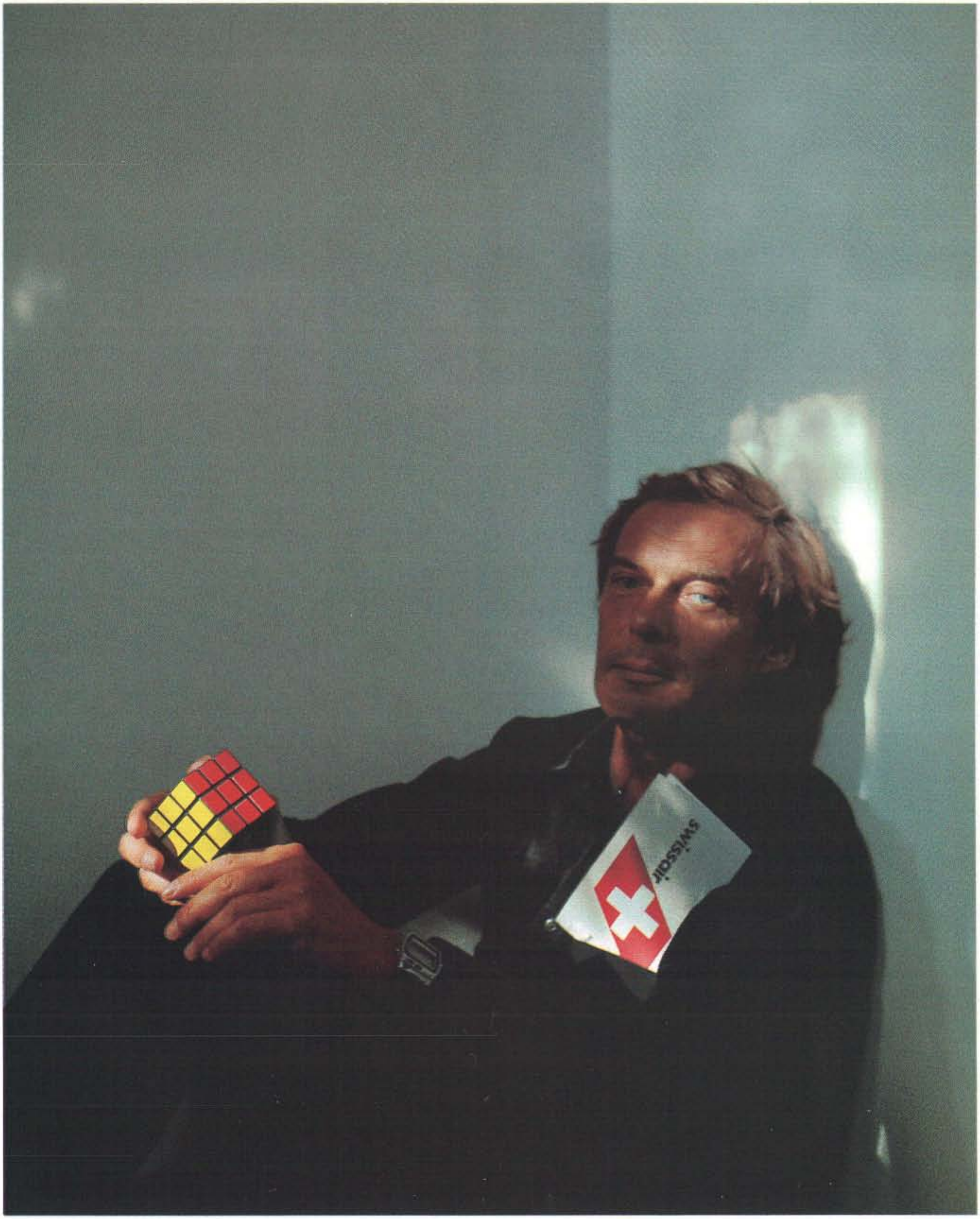
Swissair Customer Portrait 116: Professor Ernő Rubik, architect and designer, Budapest.



Professor Ernő Rubik, inventor of the Rubik Cube, always looks for reliability and precision in his inventions. And that's what impresses him about Swissair. Being a businessman, he prefers Business Class. And now that Swissair's brand-new MD-11 has created new standards of comfort on long distance flights, it's a level of service that just clicks into place.

Focused Ion Beams

Liquid-metal sources, their conical shape generated by electrostatic fields, produce charged atoms that can cut away and rebuild circuits on a microscopic scale

by Jon Orloff

In the days before the invention of integrated circuits, a technician wielding pliers and a soldering iron would troubleshoot electronic equipment, replacing failed components, repairing broken connections and eliminating short circuits. Today a million or more transistors, resistors, capacitors and connecting wires can fit on a single square centimeter of silicon. Traditional repair and modification methods have clearly been rendered moot.

Focused ion-beam systems, however, can now modify integrated circuits by cutting or adding wires only a micron across. These versatile tools are based on the liquid-metal ion (LMI) source, one of the brightest sources of charged particles yet invented. This source, coupled with an ion optical system, can produce a focused, steerable beam of charged atoms whose energy may range from one kiloelectronvolt to several hundred. The atoms can perform a variety of ultraprecise tasks: micromachining—the fabrication of micron-size objects as if by a miniaturized milling machine; maskless implantation of dopants to activate semiconductor materials; analysis of the elemental composition of surfaces; nanolithography; and the repair of optical and X-ray lithographic masks.

In its simplest and most commonly used form, a liquid-metal ion source consists of little more than an electrode and a needle whose end radius is about 10 microns. The needle is coated with a metal that has high surface tension and low vapor pressure. When a voltage is applied to the electrode, the resulting electric field stress distorts the liquid surface; the stress is opposed by surface tension, which tries to minimize the surface area of the liquid. In response to the competing forces the tip assumes a conical shape.

The electric field stress and the surface tension are both proportional to the liquid's surface curvature, and so they both become large at the apex of the cone. In a mathematical cone the forces would become infinite at the apex. But when the electric field reaches a value of 100 million volts per centimeter (10 volts per nanometer in somewhat less unsettling units), metal atoms begin to ionize. The resulting ion current ranges from a few nanoamperes to tens of microamperes.

The radius of curvature of the liquid must be only a few nanometers to generate such a high electric field; as a result, the LMI source is almost a "point" ion source. This is the beauty of the device: whereas other ion sources are extended in space and so require complex optical systems to focus their emission down to a small spot, the limited extent of the LMI source means that its optical image must be reduced only modestly to focus ions into a very small spot. Focused ion beams require much less complex optics than do typical electron beams, even when such realities as the mutual repulsion of the ions and the inevitable spherical aberrations are taken into account [*see box on page 78*].

Indeed, a very small optical system—less than 10 centimeters across and 30 centimeters long—can focus a substantial fraction of a nanoampere of current from an LMI source onto a spot that is only 50 nanometers across. The resulting current density, several amperes per square centimeter, is roughly the same as the density of current flowing through typical solid wires in an electronic circuit. It is easily sufficient for scanning ion microscopy or for micromachining.

The conceptual ancestry of the LMI source goes back to the field ionization source developed by Erwin W. Müller in the 1950s. The field ionization source, which simply consists of an atomically sharp tip at whose point an electric field ionizes gas atoms, has long been an important tool in surface physics because it can produce images of individual atoms in the tip.

The LMI source as it exists today grew out of an effort to build attitude-control motors for space vehicles. In the early 1960s Victor E. Krohn, Jr., then at TRW, Inc., made an extensive study of sources capable of producing small, electrically charged droplets. He found that metals with a high surface tension had the undesirable tendency (for a rocket engine) of producing ions rather than droplets. A few years later Krohn turned his interest from the macroscopic to the microscopic and, along with others, began studying LMI sources for the purpose of marshaling ions into high-intensity, focused beams.

In 1975 Roy Clampitt and his coworkers in England began demonstrating a liquid-metal ion source. Their device was rapidly adapted to the production of focused ion beams. Although a number of groups, including Riccardo Levi-Setti and his colleagues at the University of Chicago and Lyn W. Swanson and me at the Oregon Graduate Institute of Science and Technology, had built focused ion-beam systems based on other ion sources, these efforts had been plagued by low-beam current. Robert L. Seliger, James W. Ward, Harry T. Wang and Randall L. Kubena of Hughes Research Laboratory demonstrated the first scanning ion microscope with an LMI source in 1978; their important work inaugurated the

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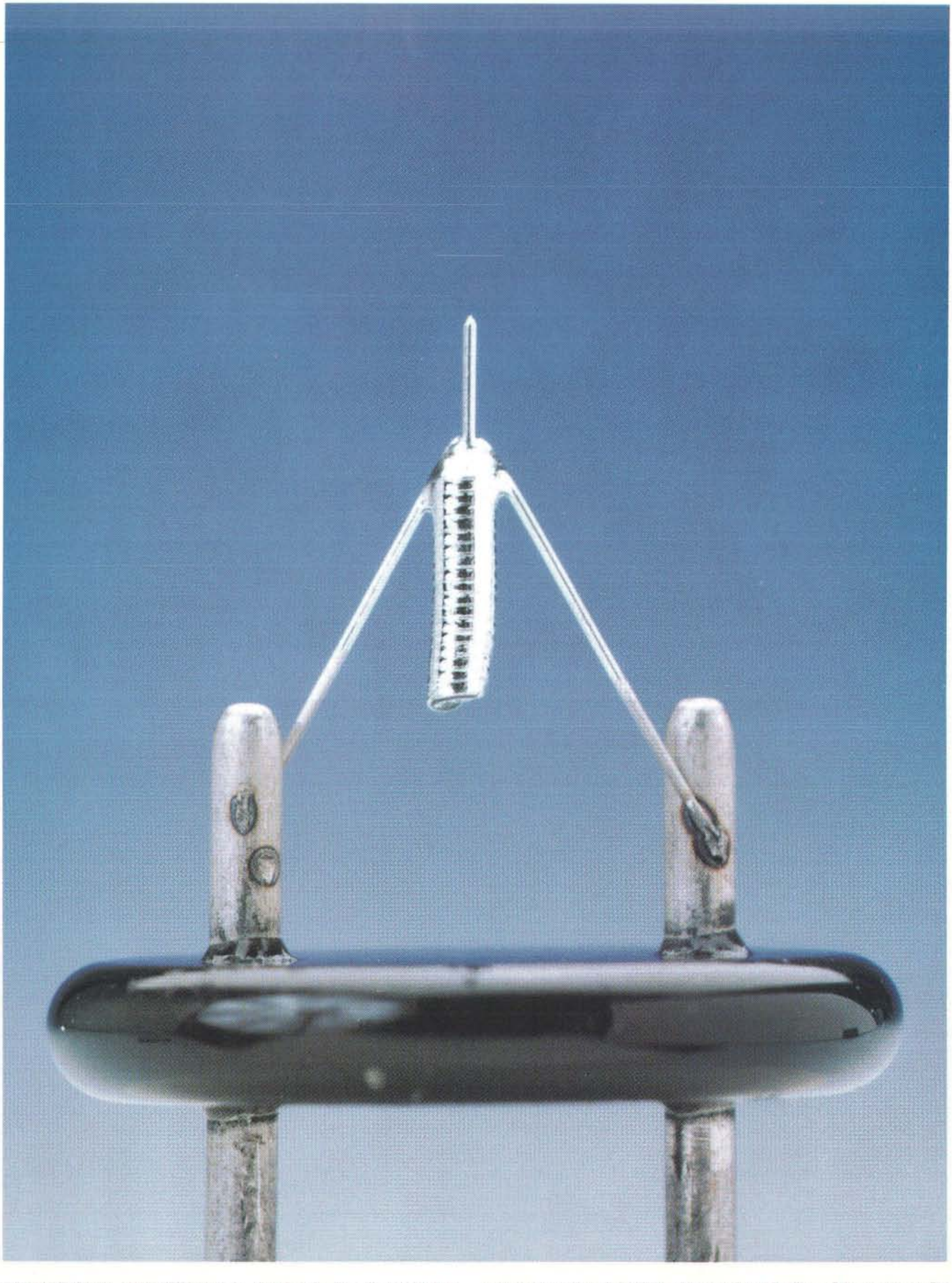


LIQUID-METAL ION SOURCE is the basis for focused ion-beam systems that perform micromachining and other tasks. The source consists of a needle, a coiled metal reservoir that supports a droplet of liquid metal, and wires that support the source, control its operating voltage, and supply current to heat it to operating temperature.

era of high-performance, focused ion-beam technology.

The possibility that focused ion beams could be applied immediately to semiconductor device fabrication was so exciting that the building of working systems outpaced the development of an adequate understanding of the physics of the LMI source operation. The imbalance led to some difficulties and to less than optimal use of focused ion-beam systems. In particular, hopes for maskless implantation of dopant elements such as arsenic or boron into silicon wafers did not become a commercial reality. Nevertheless, many other applications were rapidly exploited.

As often happens with new scientific developments, applications of the liquid-metal ion source have arisen unpredictably. In the late 1970s and early 1980s, efforts at the Oregon Graduate Institute had been aimed at measuring the properties of LMI sources as well as at developing focusing optics for point sources. My colleagues Swanson and Anthony E. Bell, along with visiting scientists David R. Kingham of the University of Cambridge and Nian-Kan Kang of Academica Sinica's Institute of Electronics, had developed a solid theoretical and experimental understanding of the sources' physics. We had also demonstrated micromachining of semiconductor devices. For example, we had opened holes in the protective passivation layers that cover an integrated circuit in order to permit probes to make contact with the aluminum wires that connect the circuit elements.

The Physics of a Liquid-Metal Ion Source

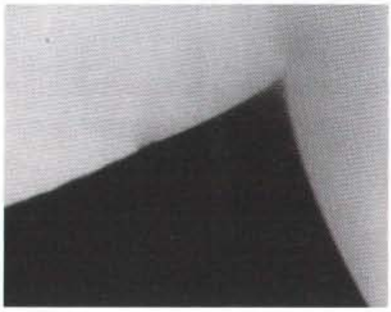
Three forces shape the surface of a liquid-metal ion source: electric field stress, surface tension and internal pressure caused by liquid flow. The first two affect any conducting liquid exposed to an electric field: the field tends to pull the liquid atoms out in the direction of the field gradient, whereas surface tension tends to hold the liquid flat. Both forces are inversely proportional to the square of the radius of curvature of the liquid surface. The sharper the point in which the metal bulges out, the stronger the electric field drawing it out farther, but also the stronger the surface tension pulling it back.

Sir Geoffrey I. Taylor, who investigated the behavior of liquids in strong electric fields in the early 1960s, showed that only a few shapes lead to a balance between electrical stress and surface tension. Most important is a cone (now known as a Taylor cone) whose half-angle is approximately 49.3 degrees. Electric and mechanical stresses hold the liquid in a conical shape indefinitely.

The electric field at the tip of an idealized mathematical Taylor cone goes to infinity, as does the surface tension. In reality, atoms evaporate from the tip of the cone, assisted by the electric field. The orbits of the electrons in the evaporated atoms are so distorted that the electrons can tunnel back into the liquid. The resulting positive ions stream away from the tip of the cone under the influence of the electric field. This process, called field evaporation, is the primary mechanism for the production of ions by the LMI source.

The radius of the tip of the cone is believed to range between one and five nanometers, but the value is difficult to determine exactly because the tip's shape is modified by the flow of liquid metal to replace atoms lost by ionization. In addition, the electric field distribution near the cone's apex is strongly distorted by the positive space charge carried by the outgoing ions, which move rather slowly during the first nanometer of travel.

The exact shape of an operating LMI source depends on the production of ions by field evaporation, the hydrodynamics of a liquid metal and the electric field above a conductor of unknown shape in the presence of extreme space charge. David R. Kingham and Lyn W. Swanson of the Oregon Graduate Institute have modeled the process by assuming an initial value for the shape of the tip and the resulting electric field and calculating the rate of field evaporation. They then calculate the ion trajectories using Poisson's equation, which determines the electric potential in the presence of space charge caused by the ions themselves. The electric potential in turn influences the rate of field evaporation. They vary the shape of the liquid until the calculations generate a consistent answer.



TAYLOR CONE, seen here in an electron micrograph made by Ben Assayag and Sudraud of the University of Paris, is a shape that yields a stable equilibrium between the opposing forces of surface tension and electrical stress that act on a liquid-metal ion source. The flow of liquid to replace atoms ionized by the electric field distorts the shape of the cone's tip into a cusp. The dark cloud visible just beyond the tip is a jet of metal above the Taylor cone.

Their analysis indicates that the ion-emitting region of the cone is indeed only a few nanometers across, although the exact dimensions depend on the approximations used in the calculation and on the current through the cone. The space charge is of the order of one million amperes per square centimeter—10 billion amperes per square meter—and so it is difficult to be sure the calculated shape is precisely correct.

Atoms removed from the end of the cone by ionization are replaced by liquid flow. An ion current of one microampere implies that about five cubic microns of atoms must be ionized per second. The tip of the Taylor cone has an area of only about ten-millionths of a square micron, and so the velocity of the liquid near the end is on the order of one meter per second.

This speed is remarkable: one meter is a billion times the end radius of the cone. If a baseball were to move a billion times its own radius in a second, a ball pitched precisely at noon, eastern daylight time, in Shea Stadium would arrive at the plate in Candlestick Park 50 milliseconds later (ignoring the effects of special relativity).

The forces generated by the flow, which can be approximated by using Bernoulli's equation, distort the Taylor cone into a cusplike shape, and as a result the liquid-metal ion source looks like a little jet on the end of the cone.

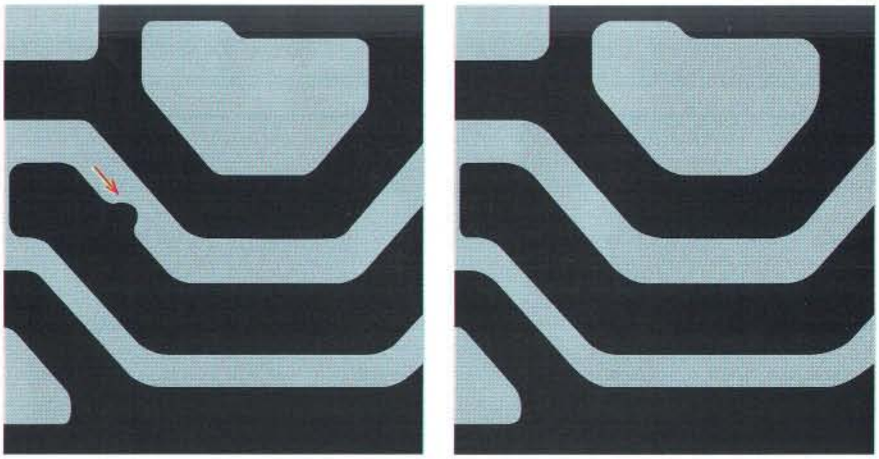
In 1984 matters took a different turn. Using a vacuum system and specimen chamber from a defunct scanning electron microscope, I built a simple one-lens focused ion-beam system that could produce spots no smaller than 250 nanometers. After verifying the system's capabilities, I began looking for applications. I rolled the system to the other end of the building, where the optoelectronics group was located. I put it in a small room and left it running with the door ajar. An operating scanning microscope always attracts attention, and sure enough, after a few weeks I was asked what it was and what it was good for.

The result was a collaboration with Richard K. DeFreez and the late Richard A. Elliott. We explored the direct fabrication of optical components for semiconductor lasers. In particular, we demonstrated that it was possible to machine new end facets and turning mirrors in the body of gallium arsenide lasers without impairing their performance. End mirrors, which reflect light back into the lasing region to amplify it, are usually made by cleaving the crystal at a predetermined spot. Turning mirrors, which deflect light out of its original plane of motion, are a crucial component of optical integrated circuits.

This work earned a citation from *Optic News* as one of the 12 most innovative advances in optics for 1987; later DeFreez and Elliott added diffraction gratings and internal mirrors (to make ring lasers) to their repertoire. DeFreez's group is still vigorously pursuing additional refinements. Lloyd Harriott and his colleagues at AT&T Bell Laboratories have also done similar work.

About the same time, Albert M. Wagner, Jr., then at AT&T Bell Laboratories, proposed using focused ion beams to repair defects in the chrome-on-glass lithographic masks that serve as patterns for integrated circuits. Ions, he suggested, could sputter away opaque defects, and they could render clear defects opaque by damaging the glass in some way, perhaps by creating tiny prisms. Later it was found practical simply to deposit carbon on a clear defect by using a focused ion beam to decompose a gas introduced into the vacuum chamber.

Focused ion-beam mask repair is a conceptually simple application because it requires relatively simple focusing optics and only low energy—25 kiloelectronvolt ions. The only drawback is that the impact of the ion beam that removes opaque defects may reduce the transparency of the underlying glass. In the case of X-ray masks, degradation of transparency is not a problem, but the masks do consist of a significant thickness of gold or tungsten on a light substrate such as boron nitride. Opaque defects must be removed very carefully, or else material removed from the defect may be redeposited on adjacent structures, changing their shape and so rendering the mask useless. Reducing the simple concept to practice has turned out to require sophisticated computer controls and considerable ingenuity.



LITHOGRAPHIC MASKS for the manufacture of integrated circuits can be repaired by focused ion-beam systems. An opaque defect (*arrow, left*) is etched away by the beam. Clear defects can be repaired by depositing carbon on them.

One application of focused ion beams has not lived up to its early promise: direct implantation of dopants in semiconductors (without resort to optical masks) to form integrated circuits. Some researchers hoped that focused ion beams based on high-current liquid-metal sources could be used to implant dopants directly into specified regions of a silicon wafer, and a number of high-voltage (100- to 200-kilovolt) focused ion-beam systems were fabricated for this purpose in the early to mid-1980s.

Unfortunately, the liquid-metal ion source does not provide enough current to make direct implantation commercially practical. Instead the technique is useful primarily for research. For example, an ion-beam system can grade the dopant level across the gate of a transistor and so tailor properties in a way that cannot be done using normal fabrication techniques. Although new devices made by focused ion beams cannot be exploited commercially, they may lead to an understanding of semiconductor physics that can be applied to circuits fabricated in a more conventional fashion.

Even if focused ion beams cannot be used to implant atoms directly, they can write lines in a resist that is then processed conventionally. John Melngailis of the Massachusetts Institute of Technology and Kubena of Hughes Research Laboratory have intensively refined this technique. Both groups have demonstrated patterns containing lines between 10 and 50 nanometers wide. Optical lithography, in contrast, cannot create lines less than a few hundred nanometers wide.

Although a high-energy beam must generally be used to ensure that the resist is completely exposed, the M.I.T. group has developed a low-energy lithographic technique. First, they write on the resist with the beam, causing exposed molecules to form cross-linked bonds. When the wafer is immersed in silicon-bearing gas, these bonds prevent the diffusion of the gas into exposed areas. The silicon in the unexposed resist hardens those areas, and so plasma etching leaves the wafer bare wherever the focused ion beam has written. This technique can compare favorably in speed with electron-beam lithography.

In the past few years, focused ion-beam systems have become widely used in the semiconductor industry. They are used primarily to analyze integrated circuits that have failed but also to modify circuits after fabrication.

Failure analysis is crucial in an industry where perhaps four fifths of the most technologically advanced chips that come off the fabrication line are no good. Before the advent of focused ion beams, it was virtually impossible to analyze integrated circuits without destroying them. Once a circuit had been fabricated, examining its interior required chemical or plasma etching to

Ion Optical Systems

The focusing of charged particles bears a strong resemblance to the focusing of photons. Instead of glass or other materials of high refractive index, however, these optical systems use variable electrostatic or magnetic fields. Magnetic lenses are typically used to focus electron beams, but such devices will not work for ions because the focusing power of magnetic lenses depends on the square root of a particle's charge-to-mass ratio. A magnetic lens for gallium ions, for example, would have to be about 350 times stronger than a magnetic lens for electrons of the same energy.

Instead ion optics requires electrostatic lenses, which consist of two or more electrodes with high voltages applied to them. The theoretical optical qualities of these systems are inferior to those of magnetic lenses, and they have long been sneered at by most electron microscopists, but their focusing properties are independent of charge-to-mass ratio. Moreover, they are very compact.

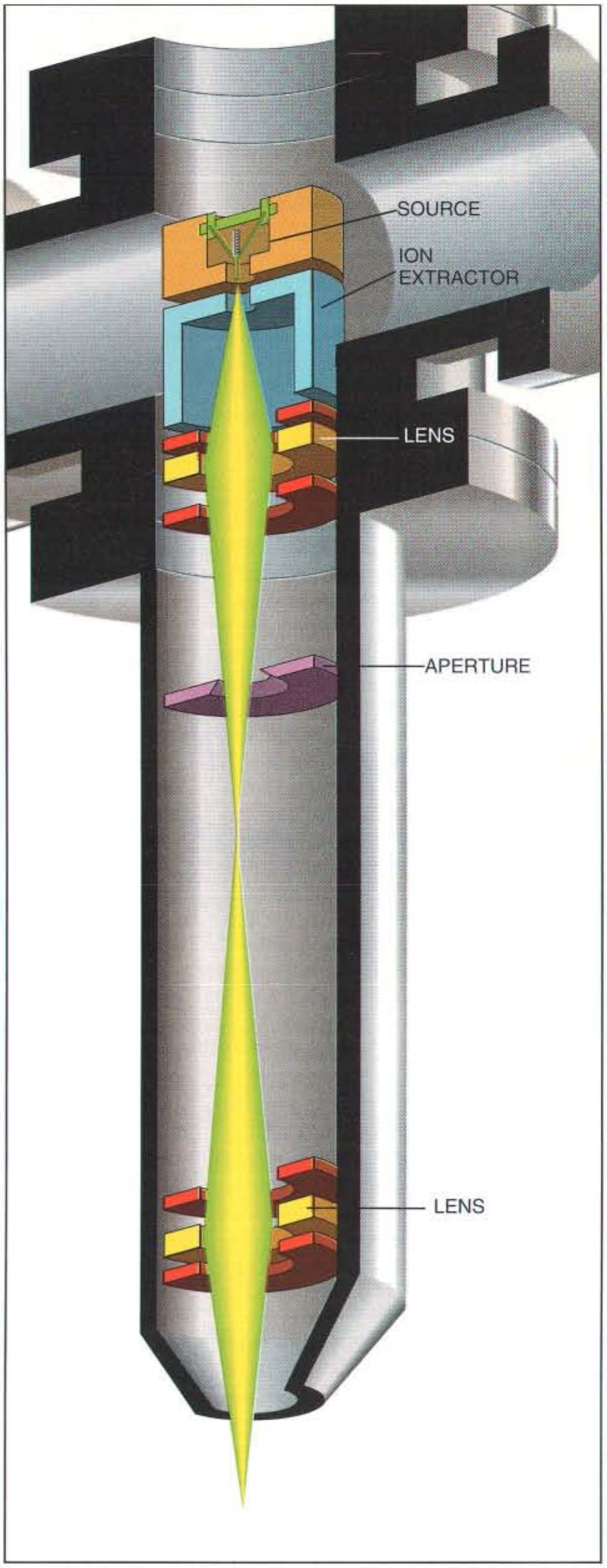
The only real disadvantage of electrostatic lenses for electron microscopy is spherical aberration—the tendency to bring particles that pass farther from the optical axis to a shorter focus than those that travel near the axis. But the overwhelming influence of chromatic aberration (changes in focal length based on the energy of the particle being focused) in most focused ion-beam systems renders spherical aberration of lesser significance, and so spherical aberration does not penalize electrostatic lenses in this application.

The chromatic aberration arises from the high density of ions just above the liquid surface. The ion density leads to an extremely large space charge, which causes the ions' energies to assume a broad distribution. The focal length of an electrostatic lens depends on the energy of the particle, and so ions of different energies are focused at slightly different points.

Space charge also perturbs the trajectories of the ions and causes the apparent size of the ion source to increase. James W. Ward and his colleagues at Hughes Research Laboratory showed that the very high current density just above the surface of an LMI source causes the ions to repel one another strongly and in a random fashion. Although the emitting area of a liquid-metal ion source is only a few nanometers across, the source as seen through the optics of a focusing column appears to be an order of magnitude larger.

The wavelength of a moving ion is so small that ion optical systems cannot be analyzed by the wave optics used to calculate the focusing and diffraction of light or electron beams. Even the largest supercomputers would take too long to solve the equations required.

Fortunately, a simpler method serves instead. Geometric optics, the kind of optics taught in high school, is the limiting case for particles whose wavelength is zero. Lens focal length, magnification and aberrations can be defined simply by solving the equations of motion of the particles through the electrostatic field, using Newton's equations of motion. In addition, Gertrude F. Rempfer and Michael Mauck of Portland State University and Mitsugu Sato of Hitachi have developed methods to find the distribution of charged particles at a focusing plane, in terms of the current density distribution of the source and the properties of the lenses. Once this distribution has been calculated, it will be possible to determine in detail the behavior of a focused beam.



ION-BEAM FOCUSING COLUMN, shown here in schematic form, measures only about 30 centimeters in height. An electrostatic lens focuses the ion beam on the target, and deflection plates control the position of the beam.

strip away the top layers. The different rates at which the elements of the circuit responded to etching made it difficult to control the process.

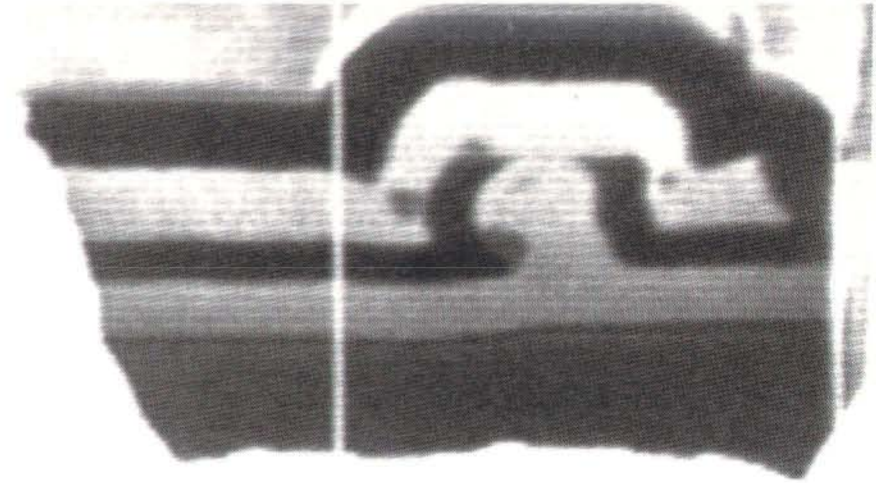
The focused ion beam, in contrast, can sputter material away from a precisely defined region without disturbing adjacent areas. Moreover, an ion beam focused to a spot only a few tens of nanometers across can simultaneously serve as a scanning ion microscope. In addition to providing a visual picture of the area being machined, the system can be equipped with probes to collect secondary ions liberated during the sputtering process. Secondary ions reveal the chemical nature of the surface. Because this method can save considerable time in failure analysis, it is of great value in circuit manufacturing. The use of focused ion beams for analytical work was initiated by David C. Shaver and his co-workers at the M.I.T. Lincoln Laboratories and by Michael Ward of Intel Corporation in cooperation with the Oregon Graduate Institute, as well as by Hiroshi Yamaguchi of Hitachi.

In addition to analyzing circuits directly, micromachining can serve as an invaluable aid to electron-beam tests of circuit function. The electron beam, which acts as an almost perfect circuit probe, works by freeing electrons from the target area. The energy of these secondary electrons depends on the electrical potential of the circuit at that point. Such measurements are extremely useful because they can determine voltages in a circuit within a millivolt or so while the circuit is actually operating. Furthermore, the beam imposes no electrical load on the circuit and does no mechanical damage.

If the point of interest is covered by a glass passivation layer, however, the measurement becomes much more difficult. The combination of buried conductor and glass acts as a capacitor whose stored charge distorts rapidly changing electrical waveforms.

Furthermore, the thickness of the glass layer blurs the electrical potential to which the electron-beam measurement responds. If two conductors carrying different signals are separated by a distance comparable to the thickness of the glass layer, it may be impossible to distinguish their signals.

The focused ion beam eliminates both problems by cutting a small hole, roughly one micron square, through the glass. The electron beam can then impinge directly on its target. Indeed, in cases where several conducting layers lie one atop the next, it is even possible to cut a series of holes, descending in size, through each conductor in turn. By this means, all the conductors may be monitored simultaneously without affecting the circuit.


MICROMACHINING by ion beams reveals the interior layers of an integrated circuit for examination. In addition to making buried structures visible, ion-beam machining can make wires accessible to point-contact probes or electronic probes.

In addition to cutting away portions of integrated circuits, a focused ion-beam system can add wires where none existed before. Groups led by Melngailis of M.I.T. and Kenji Gamo of Osaka University have demonstrated such a technique: they spray a metal-bearing gas over the surface of a chip while simultaneously directing a focused ion beam onto it. The gas decomposes under the impact of the ions, leaving wires wherever the beam impinges. The conductivity of these metal wires is not as high as that of wire deposited by more conventional methods; instead it is roughly equal to the conductivity of metal-silicon alloy wires known as silicides, which carry short-range signals in integrated circuits.

This new technique is used to repair circuits or to modify them for specialized tasks. (Current customization techniques are either time-consuming or impose unacceptable restrictions on circuit design.) The ability to add wires is particularly important in failure analysis—once the apparent source of a circuit's failure has been found, it is crucial to determine whether the circuit actually functions when the trouble has been repaired. Ion-beam rewiring could also help put a complex, hard-to-manufacture chip back in service.

As workers gain more experience with focused ion-beam sources, they will be able to fabricate structures more accurately. They will also be able to control the qualities of the material deposited by ion beams in a more refined manner than is now possible. The development of low-energy focused ion beams, which accelerate ions to energies of only one kiloelectronvolt or less, will reduce the disorder created as the beam impinges on a surface. This will permit the fabrication of higher-conductivity wires and so make ion-beam deposition applicable to a wider range of problems.

In the near future, focused ion-beam systems perhaps no larger than a desk could perform a combination of lithography, micromachining and deposition. Such systems would be capable of manufacturing—at least on a small scale—complete electronic and optical circuits with minimum dimensions of less than 10 nanometers. The remarkable capacity of focused ion beams for circuit analysis and repair implies that every chip such a manufacturing facility turned out would be a working one. Meanwhile devices one tenth the size of the smallest ones now achievable would permit 100 times as many elements to be placed on a single chip. Such ultra-large-scale integration could render the largest supercomputers of today mere components of a future silicon system.

FURTHER READING

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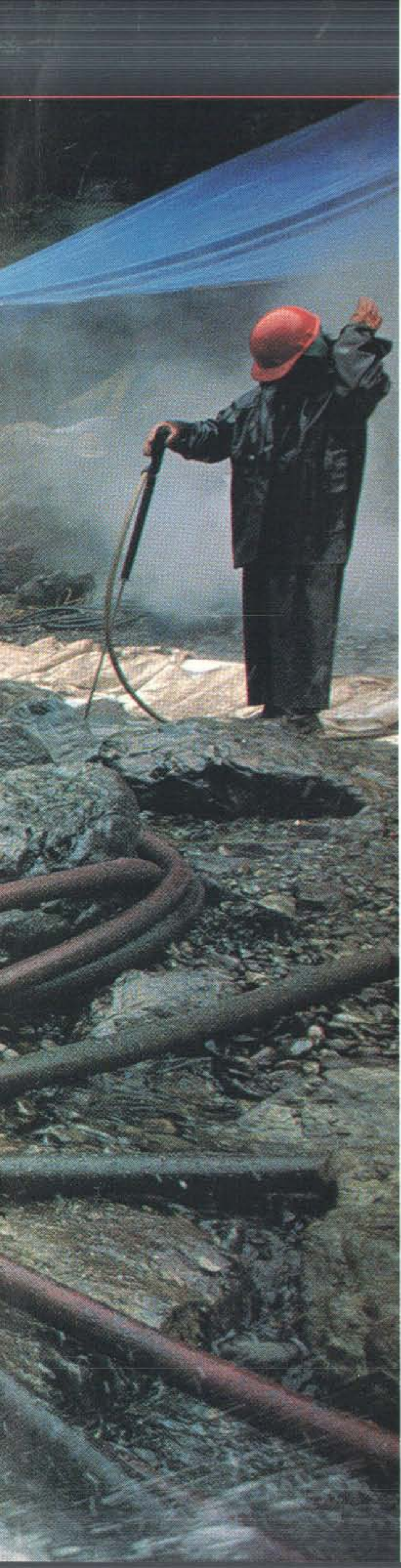
TRENDS IN ENVIRONMENTAL TECHNOLOGY

SOILED SHORES

by Marguerite Holloway, *staff writer*



Cleanup technologies, from hot-water washing to fertilizer, were applied to the mess left by the *Exxon Valdez* oil spill. But nature, it seems, fared better on its own.

Snaking up the face of the steep rocks that rise from the waters of Prince William Sound to meet a mossy coastal rain forest is a demarcation that fascinates Jonathan P. Houghton. On the left, the rocks below the high-water mark are thinly covered by closely cropped light green-brown rockweed, or *Fucus,* and little else. Immediately to the right, the *Fucus* is plusher and grows higher on the rock face. Tucked among its long brown tassels is the abundance of life common to this subarctic Alaskan habitat: encrusting pink coralline algae and encrusting red algae, sea sac, limpets, Sitka periwinkles, drills and hermit crabs.

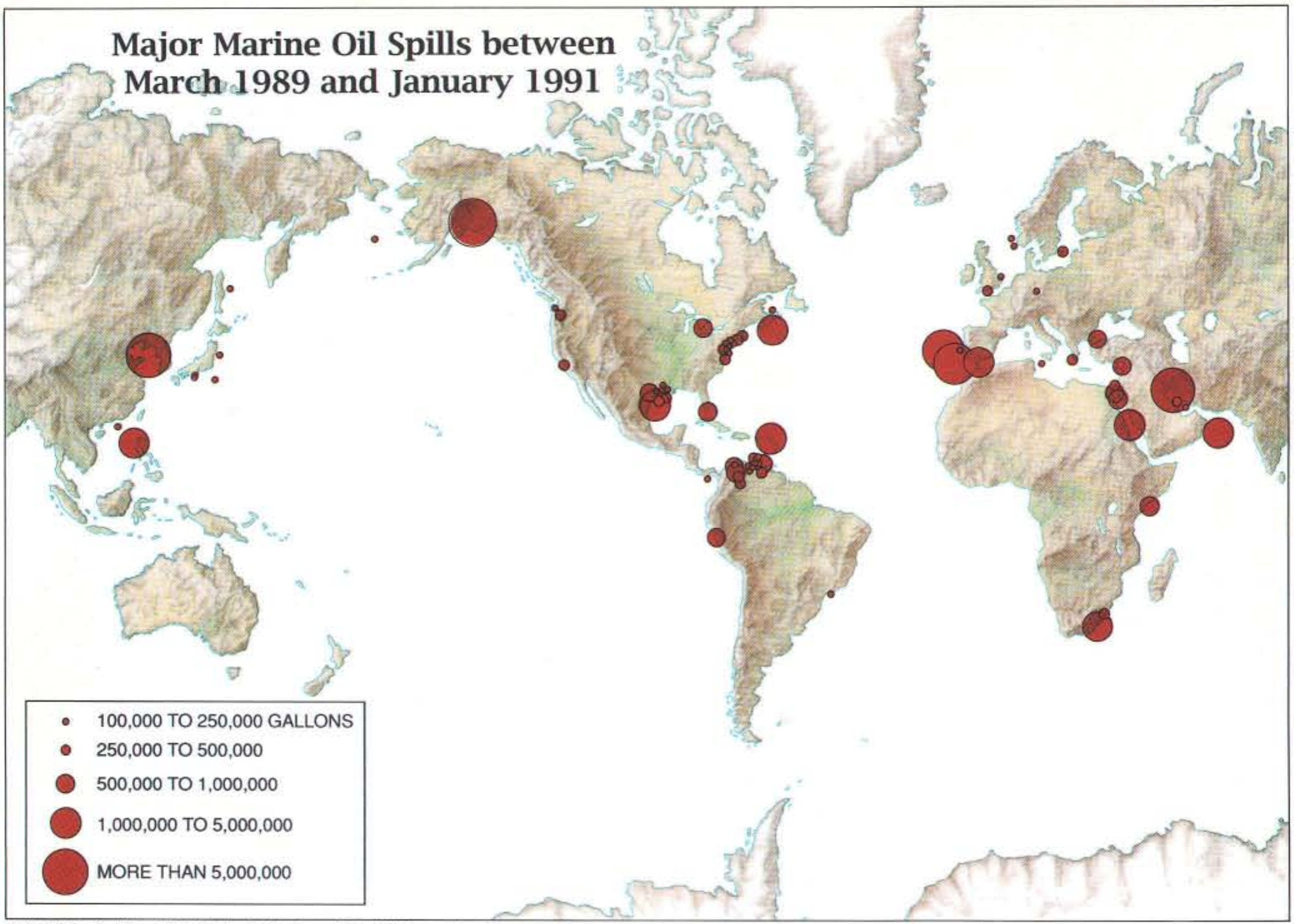
Leaping from one slippery rock to another—apparently forgetting his bruising fall while doing just the same thing a few days before—Houghton points to the *Fucus*-drawn line. The marine biologist, under contract to the National Oceanic and Atmospheric Administration (NOAA), believes the rocks on the left were blasted by pressurized 140-degree-Fahrenheit water in an effort to remove the oil that washed ashore from the *Exxon Valdez* spill in March of 1989. In contrast, he says, the rocks on the right escaped hot-water treatment and were cleaned by waves and natural processes.

The ragged line on the rocks does more than separate one seemingly fertile intertidal region from a less diverse one. It divides Houghton and his colleagues from some other scientists in a debate about the methods used to clean up shores soiled by oil. The NOAA researchers have found that habitats treated with hot water take longer to recover than those left untreated, a determination that is supported by other studies. But scientists working for Exxon and officials of the Alaska Departments of Environmental Conservation and Fish and Game argue that the ecosystem suffers greater damage if such measures are not taken to remove oil.

The *Exxon Valdez* spill, devastating in its ecological, sociological and financial costs, was much more than an environmental violation. It is estimated to have killed thousands of marine mammals and more than a quarter of a million birds. It threatened subsistence livelihoods and may have altered the ecosystem of Prince William Sound for decades. But it also tore off the veil of preparedness worn by U.S. industry and by federal and local governments. Technology proved unable to contain or contend with the spill, and it is likely to prove inadequate again.

The 11-million-gallon *Exxon Valdez* accident was only one of

WASHING BEACHES with pressurized hot water, crews attempt to remove oil from the shores of Prince William Sound after the Exxon Valdez *spill. Unfortunately, the technique also destroys any surviving marine organisms.*


Major Marine Oil Spills between March 1989 and January 1991
● 100,000 TO 250,000 GALLONS
● 250,000 TO 500,000
● 500,000 TO 1,000,000
● 1,000,000 TO 5,000,000
● MORE THAN 5,000,000

SOURCE: Golob's Oil Pollution Bulletin and World Information Systems, Cambridge, Mass.

many widely publicized recent shocks to the world's oceans. Since the Alaskan spill, oil has poured into waters off St. Kitts, Rhode Island, Texas, New York, New Jersey, California, Morocco, France, Italy, Washington State and the Great Barrier Reef of Australia. Each of these accidents was in turn dwarfed by the deliberate emptying of 250 million gallons into the Persian Gulf [*see page 86*], an ecosystem already faltering under the weight of the 80 million gallons of oil spilled in 1983 during the Iran-Iraq war.

Although the full environmental damage wreaked by each of these major discharges may never be known, the oil represents one more threat to marine organisms that already contend with urban runoff, industrial waste, sewage effluent and thousands of smaller oil spills. According to the U.S. Coast Guard, tanker accidents currently contribute only 5 percent of the estimated 2.3 million tons of petroleum hydrocarbons entering the seas each year—down from 12.5 percent in 1985. Still, the spills are acute, concentrated injections of oil, and they tend to galvanize public concern. And such accidents may become more frequent. U.S. oil imports are expected to grow 50 percent by the year 2000—most of that oil will be delivered by tankers, according to a recent National Academy of Sciences (NAS) report on tanker design.

As one of the most studied oil spills to date and as the major impetus behind the Oil Pollution Act of 1990, the *Exxon Valdez* incident has catalyzed a reevaluation of cleanup technology. The findings of scientists assessing the damage to the Sound and the subsequent recovery of the environment may shape the direction of cleanup and prevention technologies for years to come, both nationally and internationally.

Nagging Question

The disaster also provided a shot of adrenaline to a flagging oil-spill response industry. Exxon pumped an estimated $2.5 billion into cleanup, the federal government nearly $154 million. In addition, the Oil Pollution Act established a five-cent-per-barrel tax on oil to create a $1-billion-per-spill cleanup fund. The oil industry also committed $900 million to the new Marine Spill Response Corporation, which plans to spend between $30 and $35 million on research and development of related technology over the next five years.

Despite the boost to industry and the outrage expressed by the public, the next big spill offers little hope of being more than a reenactment of chaos. "Next time I hear about an oil spill in a place that I love, I am going to get a bottle of gin and get snookered so that I can't respond," declares Dennis C. Lees of ERC Environmental and Energy Services Company in San Diego, Houghton's partner in the NOAA study.

Successful beach cleanup, the focus of Exxon's efforts, remains an elusive goal. The company's attempt to purge more than 1,000 miles of rugged shoreline—more than had ever been previously contaminated—encompassed hot- and cold-water washing, backhoeing and tilling, as well as manual oil removal. It also involved the largest effort to date to increase the natural rate of oil degradation.

Yet two and a half years after the accident, a nagging question remains. Was the cleanup worth the cost, both ecological and financial? Many areas of the Sound now appear to be oil free (except for persistent pockets of crude oil that have formed beneath the surface of the beaches). But some scientists argue that nature—not Exxon—should take the credit.

Northwest Bay, the site of the dividing line on the rocks, was one of the most vigorously treated areas of the Sound. This summer, as the NOAA research vessel enters the small bay in the afternoon drizzle, the captain says, "Nothing lives here. It's a dead place." At one time during the summer of 1989, the bay was so filled with boats bringing in beach crews and with Exxon vessels such as the *Maxi Barge* and the *Omni Barge,* which could generate and direct vast quantities of pressurized hot water, that Houghton's crew could not even find a place to drop anchor.

"Oil was dripping off everything, running in rivulets through the rocks, filling tidal pools," Houghton says of his first visit, just after the spill. The senior biologist at Pentec Environmental, a consulting firm in Edmonds, Wash., was then working with Lees under contract to Dames & Moore (a consulting firm hired by Exxon) to study the biological impact of various cleanup efforts.

When Houghton returned that May, *Fucus* seemed to be thriving—despite the heavy oiling. "I was amazed to see that under the slick in the tidal pools there were still fish alive, as well as hermit crabs and even sea stars," he says. Houghton and Lees reported that they continued to see abundant intertidal life in uncleaned areas three and four months after the spill.

Because organisms from all the major species had survived, Houghton and Lees recommended against indiscriminate hot-water washing. Instead they supported gentler approaches, such as low-pressure, cold-water washing and the manual removal of pooled oil or tar. Their contract with Dames & Moore was not renewed. For the past two years, the scientists have led a team of NOAA researchers to Prince William Sound to evaluate the recovery of intertidal plants and animals.

According to their report, hot-water washes can do more than sterilize. Oil loosened by the process is washed down from the upper stretches of the beaches—often harsh areas where few organisms are found or where oil-tolerant species, such as barnacles, rockweed and mussels, live—into the habitats of relatively sensitive clams, marine worms and crustaceans. The study also reports that the reproduction and growth of eelgrass, an important nursery for fish and shrimp, seem to be impaired by oil contamination.

The water can wash away more than oil. The report states that pressure as great as 100 pounds per square inch destabilizes gravel and sand beaches. Shifting sediments then suffocate clams and worms, impeding recolonization. Houghton notes this beach disturbance by quizzing his crew members.

"What happened to that rock?," he asks while at Northwest Bay, indicating a large boulder, yellow on its upper half, white down below. No one answers quite correctly. The yellow hue comes from older barnacles, explains Houghton, assuming the air of a professor whose class has disappointed him. The white color indicates the presence of young recently settled. The shifting beach exposed the bottom part of the boulder over the winter, allowing it to be colonized, Houghton adds.

"I'd Do It Again"

The NOAA conclusions are far from surprising. In 1985, and even before, scientists recommended against hot-water and pressurized treatment. "It kills any animals that are still alive, and it has the tendency to work oil into the sediments further," says June Lindstedt-Siva of the environmental sciences division at ARCO. Recovery of ecosystems after such disasters as the 68-million-gallon *Amoco Cadiz* spill in 1978 off the coast of Brittany suggested that in some cases the environment was best left alone.

Although the NOAA findings are generally not contested, the agency's recommendation against any such treatment has been rejected by Exxon scientists and by Alaska state officials. Hot-water washing "was damaging, no doubt about it, but it was the only approach we had. I'd do it again," says Mark N. Kuwada, a biologist with the Alaska Department of Fish and Game.

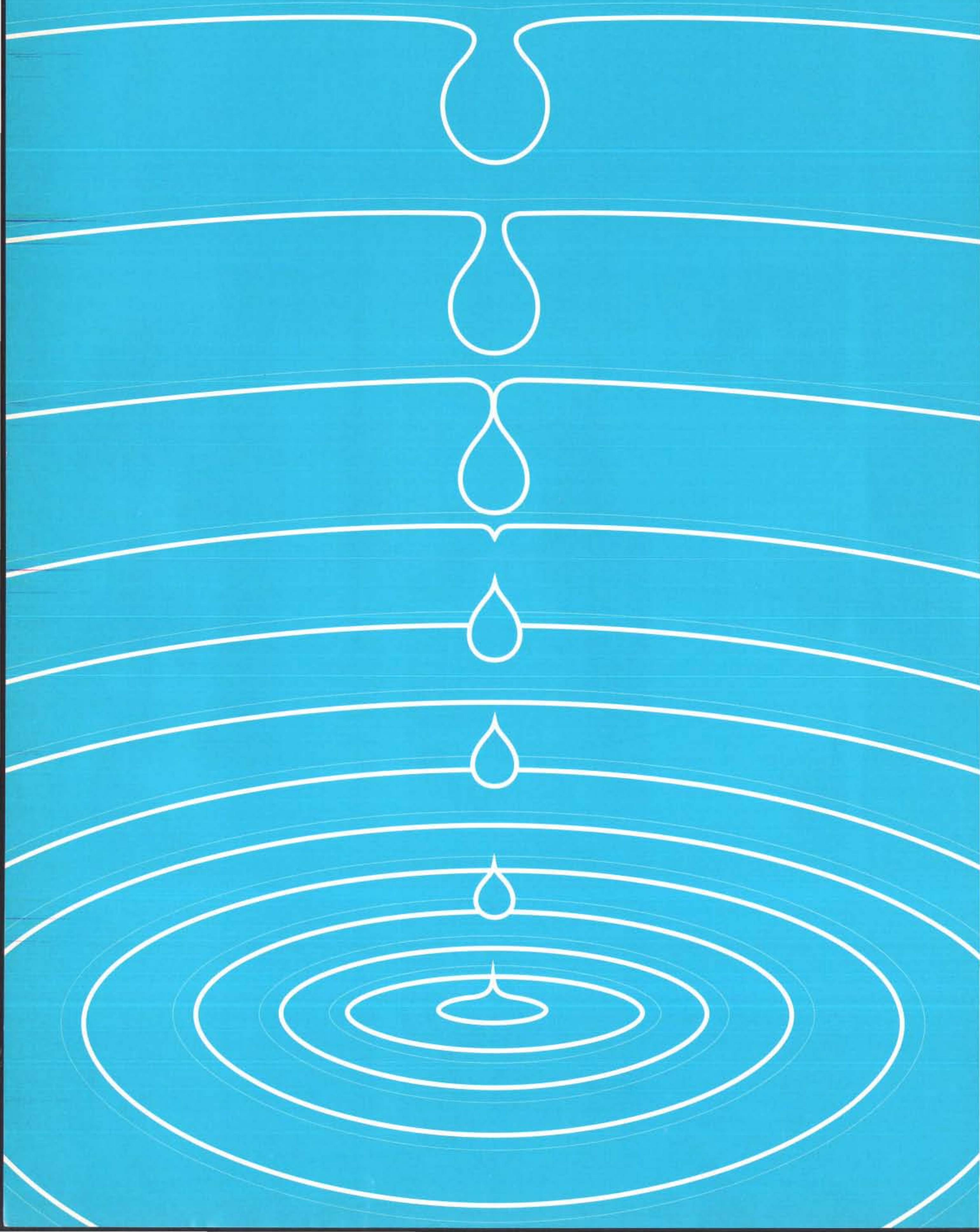
During the first summer, Kuwada says, the state wanted to ensure that breeding sites for sea lions and seals were cleaned. And despite the observations of Houghton and Lees, Kuwada and others argue that most of the intertidal life had been suffocated by oil, so that hot-water washing did not add insult to injury—it washed over a graveyard.

This summer Kuwada's concerns are different, as he demonstrates at a beach on Knight Island, one of the largest islands in the Sound. Stalking the beach, armed with a shovel, Kuwada prospects for oil. His shovel scrapes against large rocks, and there, pooled between big boulders, lie clots of thick brown ooze. In the afternoon sunlight, the smell of hydrocarbons suddenly wafts up. Without hot-water washing, Kuwada asserts as he crouches down to point at the goo, even more subsurface oil would be present today.

While scientists recognize the persistence of subsurface oil, they disagree about the remedy. The state advocates backhoeing beaches to remove it. Jac-

DIGGING FOR OIL this summer in Prince William Sound, Mark N. Kuwada, a biologist at the Alaska Department of Fish and Game, unearths subsurface crude.

C&C Computers and Communications



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queline Michel of Research Planning, Inc., in Columbia, S.C., disagrees. "My basic opinion is that if the oil is in the subsurface and hasn't come out in the last two years, its rate of release is going to continue to be slow," says Michel, who is studying the effects of cleanup on beach geomorphology for NOAA.

Studies of other spills indicate that oil remains buried for different lengths of time, depending on the ecosystem where it washes ashore. For example, a barge spilled 180,000 gallons of oil into Buzzards Bay, Mass., in 1969. Twenty years later researchers from the Woods Hole Oceanographic Institution (WHOI) who are studying a marsh on the bay found undegraded oil in a sample of the densely packed mud. "An animal burrowing into the still contaminated sediments would be exposed to oil concentrations capable of lethal effects," reports John M. Teal, a biologist at WHOI.

In contrast, there are few marshes or bogs in Prince William Sound; the rough cobbles or gravel and sand of most beaches could allow for greater aeration and therefore greater degradation. Yet, according to Robert W. Howarth, an aquatic ecologist at Cornell University, oil spilled onto a cobble beach in the Strait of Magellan was still present seven years later—ostensibly because the beach was not exposed to powerful waves. Arguments about the biological effects of the oil that lies beneath the beaches of the Sound cannot currently be measured against facts—to the frustration of many scientists. Any data indicating sublethal or lethal impacts on organisms are being withheld so they can be used in court [*see box on page 93*].

The impact of the *Exxon Valdez* cleanup has made many scientists outspoken advocates of incorporating ecological criteria into oil-spill response plans. "We have been successful in getting people to recognize that oil lasts for a long time, but perhaps the pendulum has swung too far in the other direction," notes John W. Farrington, WHOI's associate director for education. "Sometimes the public now overreacts to oil spills." Others agree that pressurized, hot-water washing should be used in areas of low biological sensitivity.

Even manual removal and low-pressure, cold-water washing can be too much for some ecosystems. Removing oil from a marsh in Brittany "destroyed portions of the marsh for much longer than it would have if we had allowed nature to take its course," Farrington asserts. Indeed, a manually cleaned marsh in the Bay of Isles in Prince William Sound looks like a wasteland these days. Oil sheens float up in footprints as the NOAA researchers slosh through it ear-

The Muddled Cleanup in the Persian Gulf

by John Horgan, *Senior Writer*

Hey, look at that!" exclaims Dave Glenn. We are standing on the shore of the Persian Gulf, some 100 miles south of Kuwait. Before us stretches what was once a salt marsh teeming with shrimp, crabs, minnows and birds. Now, in mid-June, the marsh looks as though it has been crushed by a tidal wave of asphalt, which in a sense it has.

Glenn, a heavy-equipment contractor from Washington State, points at a shrub poking out of the ooze. From its tar-encrusted crown extend a few pale green sprigs, smaller than a baby's pinky. "Those weren't there the last time I was here," Glenn says hopefully.

You need sharp eyes to find signs of hope in the aftermath of the biggest oil spill in history. The disaster sprang not from negligence or misfortune, as most spills do, but from malice. On January 19, three days after Allied planes started bombing Iraq, Iraqi soldiers let oil gush from Kuwait's Sea Island Terminal. Later, more crude spilled from a refinery in Khafji, Saudi Arabia (the site of the first major battle between Iraqi and Allied soldiers), and from Iraqi tankers. It is still unclear whether—or to what degree—Allied bombing contributed to the spills.

Initial estimates of the spill's size ranged from more than 500 million gallons to less than 50 million. The estimate has now stabilized at 250 million gallons. That is almost twice as large as the estimated output of the previous world record holder, an offshore Mexican well called Ixtoc 1 that blew out in 1980. It is more than 20 times larger than the *Exxon Valdez* spill of 1989.

Nature limited the oil's reach. The Gulf's counterclockwise current carried the oil south, down the coast of Saudi Arabia. Then, in March, a westward wind blew the slick toward shore just north of a peninsula called Abu Ali. The hook-shaped spit of land acted as a natural boom, preventing most of the oil from moving farther south. Although tar balls have reportedly washed up on Bahrain, Qatar and even Iran, the amounts are not thought to be significant.

Saudi Arabia, on the other hand, was left with some 350 miles of shoreline—stretches of sandy and rocky beach interlaced with marshes and tidal flats—awash in crude. Although visually stark and largely uninhabited by humans, the contaminated region sustains large populations of marine organisms.

CNN FACTOR. On paper, the response to the spill has been a marvel of international cooperation. Beginning in January, oil-spill experts from more than half a dozen nations—including the U.S., the U.K., the Netherlands, Germany, Australia and Japan—rushed to Saudi Arabia to help. But when I visited the headquarters of the spill-response coalition in Dhahran, Saudia Arabia, in June, workers privately criticized virtually all aspects of the response. "I'm not happy with any large-scale operation I've seen," said a U.S. Coast Guard officer.

Some participants accused the Saudis of being indecisive, parsimonious and callous toward their own environment. "If CNN hadn't been broadcasting this spill, the Saudis wouldn't have done squat," one American official said. The Saudis, for their part, suspect contractors of trying to gouge them and scientists of trying to use their country as a laboratory for untested cleanup techniques. Moreover, the Saudis point out that they did not cause the spill and therefore should not have to pay for cleaning it up.

So far only one project seems to have been completely successful. During the war, workers quickly deployed booms, nets and skimmers to protect water-intake pipes of Saudi desalinization plants and refineries, which were crucial to the war effort. After the war, somewhat more slowly, the coalition began recovering oil still floating in the Gulf. The nominal head of the effort was Saudi Arabia's Meteorology and Environmental Protection Administration (MEPA). But the bulk of the recovery work was done by the Saudi Arabian Oil Company, or Aramco, which owns much of the contaminated land and is an extremely powerful force in Saudi Arabia. "It's a kingdom within a kingdom," one contractor said.

Aramco's behavior angered some other workers. The company refused to allow MEPA contractors or even U.S. Coast Guard observers onto its land. One contractor also charged that Aramco exaggerated its recovery estimates by claiming that its 6,000-gallon tanker trucks actually held 10,000 gallons.

At any rate, by June Aramco and MEPA said they had scooped more than 80 million gallons of crude from the water. Even if the actual amount was only half that great, as some observers believed, it would still represent the most oil ever recovered—both in absolute and percentage terms—from a major spill.

Ironically, the success of the recovery effort was made possible by the total failure to protect bays and inlets. Some areas were so swamped that workers could simply drive up to the shore and pump the oil directly into trucks. "You could have bulldozed the entrance to some marshes to protect them," said John H. Robinson, who is directing activities of the U.S. National Oceanographic and Atmospheric Administration (NOAA) in the Gulf region. "It's too bad something like that wasn't done."

The Saudis now face another problem: what to do with the recovered oil. Most of it has been dumped into pits dug into the desert. Aramco has refined some reclaimed crude, but the extra steps required to remove salt water and debris make the process uneconomical. Two other proposed disposal methods are burning and "farming," which calls for sprinkling the oil over the desert and then turning over the sand. The oil may also simply be left in the pits, where, some observers fear, it may contaminate the groundwater.

P.R. PLOY. Smaller-scale efforts have also had ambiguous results. During the war, for example, a Saudi conservation group established a bird-cleaning center at Jubail, just south of Abu Ali. The center provided poignant television footage, but fewer than 20 percent of the 2,000 or so birds taken to the center survived the cleaning process. MEPA has estimated that at least 20,000 to 30,000 other birds, including cormorants and grebes, were killed by the spill.

One NOAA official called the bird-cleaning effort "a P.R. [public relations] ploy" that wasted limited resources. The most humane course of action to take with an oiled bird is to "crank start it," the official said, using a term for wringing a bird's neck. (The center's results might have been better if Islamic "religious police" had not forced it to segregate male and female volunteers, triggering numerous resignations.)

Another high-profile project involved Karan Island, a mound of sand north of Abu Ali that the spill drenched in crude. The island, although just over a mile long and a quarter-mile wide, is an important nesting site for seabirds and for two endangered species of sea turtle: the hawksbill and the green turtle.

With funding from the International Maritime Organization (IMO), a branch of the United Nations, a Scottish contractor scraped up some oily sand and dumped it into a pit only a few hundred feet from the shore; scientists worry that the oil may percolate back to the beach, if not this year, then perhaps in years to come. Workers simply pushed clean sand over other sections of blackened beach; by August, the tides had reexposed the oil. "It was not the ideal way to do it," one Australian official noted dryly.

Contractors funded by the IMO also tried to salvage a grove of rare black mangroves just north of Abu Ali by rinsing the trees with sprinklers and hoses. Unfortunately, by the time the project began, oil had already irrevocably clogged tiny respiratory pores in the roots of the mangroves. Almost all of the trees are expected to die.

The Saudis have been inundated with advice on how to treat salt marshes, which represent perhaps the most productive and important ecosystems affected by the spill. The oil-soaked mats of algae lining the bottom of the marshes sparked one particularly heated exchange. A contractor advocated scraping up the blackened slime, while an Australian biologist pleaded that it be given a chance to recover. When the contractor asked, "What the hell is the use of algae?" the biologist screamed, "What the hell is the use of humans?"

As a compromise, MEPA has tested various cleanup techniques on small sections of marsh. A project overseen by Glenn, the heavy-equipment contractor, called for bulldozing a barrier around a contaminated marsh and then flooding it with water. As the sun heats the water, oil breaks free

CASUALTY OF WAR: 30,000 birds may have been killed in the Persian Gulf spill.

from the bottom and from plants and can be skimmed off.

All the methods for cleaning marshes have potential drawbacks. The approach tested by Glenn, for example, can cause the water to become so hot and, as it evaporates, so salty that it kills anything still living in the marsh (except, apparently, the bush with the pinky-size sprigs). Officially, MEPA plans to assess the results of these pilot projects and then to recommend a treatment for oiled marshes this fall. Privately, MEPA officials predicted that the decision would be to do nothing.

BITTER OVER BUGS. Aramco, apparently too impatient to wait for MEPA's studies to be completed, simply bulldozed over marshes bordering its land. When MEPA protested, Aramco threatened to pull out of the cleanup effort entirely, and MEPA backed off, according to a Saudi contractor.

The Saudis have rejected proposals to introduce oil-consuming bacteria into the Gulf. That decision has bitterly disappointed biotechnology companies such as the British Alpha Biological Treatment Services Ltd, which sent a salesman to Saudi Arabia in March. (By June, the salesman was in Kuwait trying to convince officials there that his "bugs" could help clean their oil-fouled desert.)

The rejection of inoculation makes sense, actually. First, the technology remains completely unproved. Moreover, the Persian Gulf already boasts a thriving community of oil-metabolizing bacteria. Oil seeps have always fed the Gulf, and in recent decades man-made spills have boosted that natural background. "Dig down a little [into a Persian Gulf beach], and you hit a tar mat from Nowruz," said a NOAA official, referring to an oil field off the coast of Iran that spilled 80 million gallons into the Gulf in 1983, during the Iran-Iraq war. "Dig a little further, and you hit another spill. It's like geologic strata."

MEPA officials have also resisted a proposal that calls for sprinkling the shoreline with nitrogen-based fertilizers, or nutrients, that could enhance the ability of the naturally occurring bacteria to reproduce and degrade the oil. The officials voiced concern that nutrients could cause algae blooms or toxic levels of ammonia, but in June, after a lengthy debate, they finally agreed to conduct tests. Contractors and scientists who had been advocating nutrients were jubilant after the decision. When I asked Mahmoud M. Nowailaty of MEPA about the tests, however, he revealed that they would be conducted not on the shore but in pits deep in the desert. If these tests were encouraging, would MEPA then approve application of nutrients on the shore? Smiling faintly, Nowailaty shook his head. "I doubt it," he said.

Of course, cleanup efforts—whether involving nutrients or lower-tech methods such as raking tar mats off the beach—will proceed only if someone pays. By late June, $50 million set aside by the Allies for the cleanup had been expended, as had $5 million from the IMO. U.S. officials indicated that the Saudis would have to pay for any future work. But the Saudi government had approved funds for only a single, small operation: the cleanup of a coastal preserve where Saudi princes like to hunt rabbits.

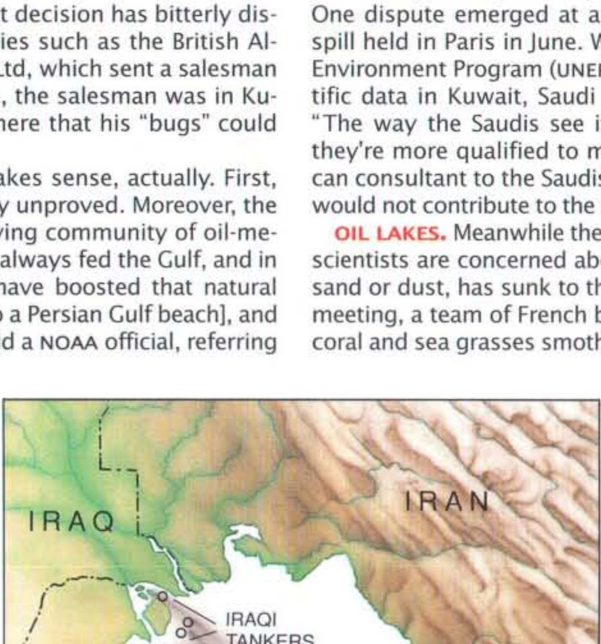
Whether or not the cleanup proceeds elsewhere, scientists hope to salvage some lessons from the spill, if only by monitoring the harm it does to the environment. The oil's effects are expected to be long-lasting, notwithstanding the Gulf's abundant oil-consuming bacteria. The reason is that, unlike Alaska's Prince William Sound, the Gulf is a shallow, low-energy system, whose current circulates only once every three years.

Inevitably, attempts to establish monitoring programs have been hampered by scarcity of funds and squabbles over turf. One dispute emerged at a U.N.-sponsored meeting on the spill held in Paris in June. When a representative of the U.N. Environment Program (UNEP) presented a plan to store scientific data in Kuwait, Saudi scientists became visibly upset. "The way the Saudis see it, the spill is their problem, and they're more qualified to manage the data base," an American consultant to the Saudis explained to me later. The Saudis would not contribute to the UNEP data base, he predicted.

OIL LAKES. Meanwhile the Gulf remains under assault. Some scientists are concerned about oil that, weighted by blowing sand or dust, has sunk to the bottom of the Gulf. At the Paris meeting, a team of French biologists showed photographs of coral and sea grasses smothered in oil. They warned that during warm spells this oil could float to the surface, causing still more damage.

In early June, moreover, MEPA reported that the Sea Island Terminal and sunken tankers were still releasing up to 100,000 gallons of oil a day into the Gulf. By August, the leaks had dwindled to an estimated 20,000 gallons a day, but Kuwait's oil fields, ignited by the Iraqis in late February, posed a potentially much greater threat.

The hundreds of wells burning in Kuwait are casting unknown quantities of soot, oil droplets, acid rain and other toxins over the Gulf. The smoke could also harm the marine environment by obscuring the rays of the sun. Next winter some species that are at the northern edge of their range, including coral and mangroves, could be wiped out if temperatures are unseasonably low, according to Andrew R. G. Price, a British biologist. Most disturbing of all are the vast lakes of oil in Kuwait, some of them miles long and more than 20 feet deep, created by ruptured wells. Officials in Saudi Arabia worry that the lakes, perhaps prodded by a rainstorm, could spew into the Gulf—triggering a spill that would obliterate the current world record.



250 MILLION GALLONS of oil released from sources off Kuwait and Iraq struck most heavily on the coast of Saudi Arabia north of Abu Ali.

ly one evening this summer. A member of the team kneels down, digging for roots to see how far grass beds used to extend into the flat, barren marsh, and finds tangles of fibers throughout but no live plants. He jokes that there are more stakes marking study and cleanup sites than there are blades of grass.

If left alone, oil degrades over time, broken down by sunlight and microorganisms. Because microbes, such as yeasts and bacteria, have evolved to consume hydrocarbons, biodegradation was the focus of another massive cleanup effort in the Sound. Scientists from Exxon and the Environmental Protection Agency sought to speed up the natural process by adding nutrients, an approach called bioremediation. Although this technique has been around for a long time, these new studies have given it a commercial boost. But, as with hot-water washing, researchers are divided about its effectiveness.

"Ecologists Go Home"

Oil-eating microbes were certainly not unknown to the Sound. According to Don K. Button, a biochemist at the University of Alaska at Fairbanks, the spruce trees that cover the islands are a source of terpenes, hydrocarbons similar to phytane and pristane, found in Prudhoe Bay crude. Microorganisms had adapted to eat these terpenes and therefore were well prepared to devour some of the cargo of the *Exxon Valdez*.

The abundance of microbes, however, makes the Sound a less than ideal test site. "If you already have a high rate of degradation, it is hard to show enhanced degradation," laments Ronald M. Atlas, a microbiologist at the University of Louisville and a consultant to Exxon and the EPA. Atlas has been studying the microbes of the Sound since 1968. That same year he remembers being driven out of the town of Valdez at gunpoint by fishermen who had bought land that they hoped the then impending pipeline would make profitable. "There were bumper stickers saying, 'Ecologists Go Home,'" recalls the banished scientist, who returned disguised as a fisherman.

Bioremediation has been used for many years in landfills and at hazardous waste sites, where researchers can regulate such factors as temperature, nutrients and levels of oxygen. At sea or onshore, scientists find these factors more difficult to control. Button, for example, argues that there is plenty of nitrogen and phosphorus in the seawater of the Sound to provide the microorganisms with nutrients. He says the bugs just need a way to metabolize the carbon in the oil. In contrast, Atlas contends that the microorganisms have plenty of easily accessible carbon from the oil and that they need proportionately more nutrients.

Exxon and the EPA followed Atlas's reasoning. During the summer of 1989, after initial trials, more than 70 miles of shoreline were enriched with fertilizers in spray and pellet form. Over the course of the next two summers, according to Exxon, some 94 miles of beach were so treated. Exxon contends that the fertilizer increased rates of biodegradation between fivefold and tenfold.

The EPA and Atlas are more conservative: they maintain that the rates were enhanced twofold to threefold. Other scientists say even twofold is optimistic. "They have done a lot of studies, and they have been hard-pressed to find any statistical difference between beaches that were treated and those that were not," Michel charges.

One initial methodological problem was that a standard for measuring degradation was rendered useless by the terpenes from the spruce trees. Pristane and phytane are normally used as a conserved standard because they are highly resistant to degradation. But the Sound's terpene-hungry microbes can easily break down these hydrocarbons. Ultimately, Exxon and EPA researchers had to rely on another hydrocarbon, called hopane, as a reference.

Other questions arose concerning the mechanism of action of one of the fertilizer products, Inipol EAP 22. During 1989, Exxon chose that product, a surface spray that is manufactured by Elf Aquitaine in France. Inipol is oleophilic, meaning that it sticks to the oil and contains oleic acid, a source of carbon. But in studies by Kenneth Lee and Eric M. Levy of the Canada Department of Fisheries and Oceans, Inipol actually slowed hydrocarbon degradation. They concluded the microorganisms preferentially consumed components of the Inipol instead of the oil.

Harm to marine organisms is also debated. Exxon and the EPA ran a series of tests to determine whether adding nitrogen and phosphorus would cause algal blooms. Despite anecdotal reports of increased filamentous green and filamentous brown algae on some beaches, neither the EPA scientists nor Exxon found increased levels of algae. Only one of four tests for toxicity to marine organisms showed that Inipol could be damaging. In that experiment, the danger to very sensitive organisms, such as oyster larvae, came 18 hours after application of the fertilizer. The reason for this one "pulse" remains unclear.

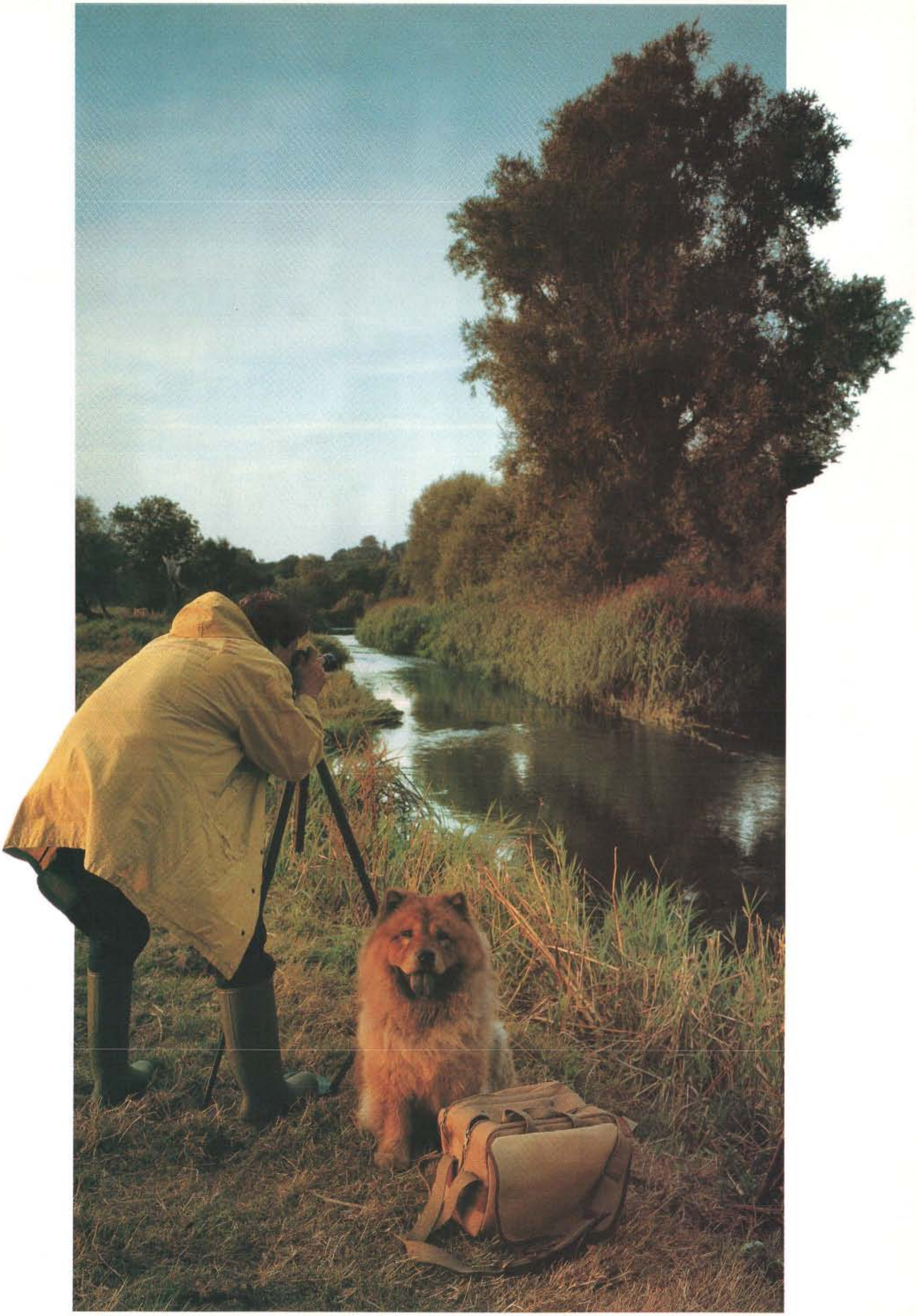
Even so, says James R. Clark, the aquatic biologist at the EPA who looked for any adverse effects of Inipol, ammonia that was released would soon be rendered harmless by dilution. "It is a matter of knowing that there is the potential for a toxic event and accepting that risk in order to enhance biodegradation," Clark explains. Michel disagrees. "Inipol has pretty high aquatic toxicity to it, higher than people like to talk about," she insists. (In contrast, little doubt exists about the danger Inipol poses to mammals. The foul-smelling product contains 2-butoxy-ethanol, which can be toxic. Crews applying the fertilizer wear respirators and gloves.)

Despite Exxon and the EPA's celebratory publicity and the photographs of a "white window" that fertilized bugs had opened on the beaches of Prince William Sound, most scientists agree that further data are needed before fertilization can become more than an experimental approach to cleanup. "I think that fertilization does offer a real chance of speeding up the natural degradation rate," says the EPA's Albert D. Venosa, who participated in the studies. "But I honestly have to share some of the skepticism that has been leveled."

Even if the rates are not all that dramatic, Atlas says getting the oil off the beach a little earlier is worth the effort. But Michel is not so sure: "You get a short-term kickoff, but in the long run, you wonder. Why bother adding more chemicals and having all that collateral damage of beach cleanup crews out there when you get to the same point anyway?"

A more aggressive form of bioremediation involves releasing exogenous, or foreign, microorganisms into the environment. This approach, called seeding, or inoculation, was tested with no success on the beaches of Prince William Sound. Tests in Galveston Bay, Tex., last year also produced no demonstrated benefit. Although the experimental conditions on the beaches of the Sound were hardly ideal for any positive results, Venosa, who conducted the studies, says he is not yet sold on the idea: "It is difficult to get those microorganisms to compete with the natural populations that have been there for millennia." Other scientists agree but say they are still optimistic about the potential of genetically engineering naturally occurring microbes.

For now, bioremediation is not considered a cleanup technology. A recent report from the congressional Office of Technology Assessment concluded that "bioremediation for marine oil spills is still being evaluated, and [its] ultimate importance relative to other oil spill response technologies remains uncertain."



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Given the drawbacks of cleaning fouled shores, scientists have sought to improve techniques designed to prevent oil from reaching beaches in the first place. One approach involves dispersants, compounds that break up oil slicks into droplets that can enter the water underneath the surface of the ocean. Degreasing agents were used to do just that in 1967 at the *Torrey Canyon* spill, where five million gallons of oil washed ashore on the southwestern coast of England. Because these detergents contained highly toxic compounds, they devastated populations of algae, limpets, barnacles and mussels.

This episode gave dispersants a bad name. But a few months before the *Exxon Valdez* disaster, the NAS released a report stating that some newly developed dispersants, although not proved entirely effective, were of comparatively low toxicity and should be considered capable of fighting oil spills. "They are an important part of the arsenal," says James N. Butler, professor of applied chemistry at Harvard University, who led the NAS review. Dispersants have been used at more than 50 spills, according to the report, but studies of their effectiveness have suffered from the lack of controls and poor documentation.

Butler points to evidence that dispersants are most effective in the two to three hours following a spill. When coupled with a storm or strong current, they can break up the oil even faster. Although dispersants were applied within 36 hours after the *Exxon Valdez* accident, "people expected the oil to disappear right away, which wouldn't happen," Butler explains. The state of Alaska did not approve further use of dispersants.

Some researchers are concerned that spreading oil into deeper waters could increase its contact with marine organisms and therefore its toxic effects. Butler notes that organisms in upper layers of water will be more adversely affected by the slick if it is not dispersed, whereas deeper dwellers will be more affected by the dispersed oil only if the water is confined. In open or deep waters, the oil will be diluted and therefore less toxic. Despite these trade-offs, Butler says the long-term effects of dispersed oil are less than those of untreated oil—at least in those ecosystems that have been studied. In particular, he says, dispersants may be best suited for use in environments that are very sensitive to oil, such as salt marshes, coral reefs, sea grasses and mangrove swamps.

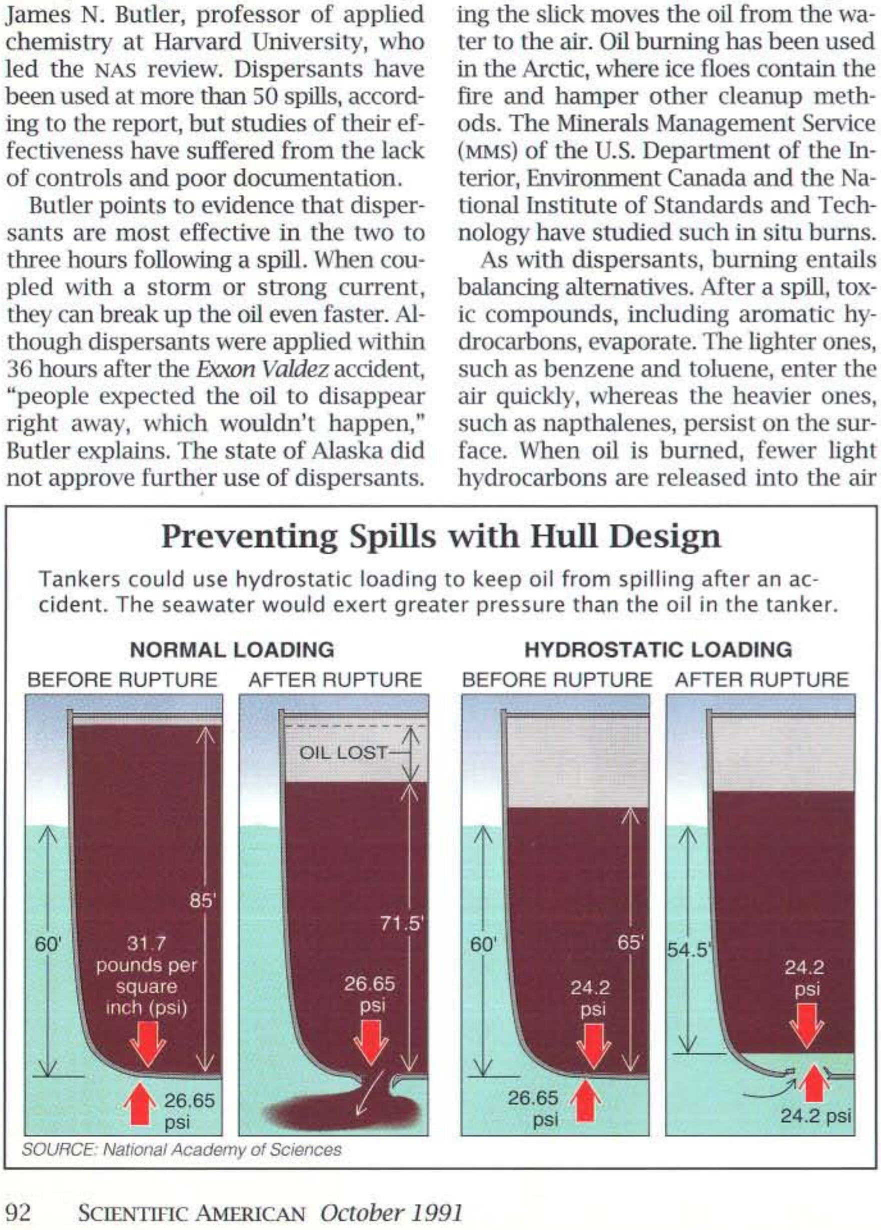
Balancing Alternatives

Dispersants work by shifting oil from one part of the water to another. Igniting the slick moves the oil from the water to the air. Oil burning has been used in the Arctic, where ice floes contain the fire and hamper other cleanup methods. The Minerals Management Service (MMS) of the U.S. Department of the Interior, Environment Canada and the National Institute of Standards and Technology have studied such in situ burns.

As with dispersants, burning entails balancing alternatives. After a spill, toxic compounds, including aromatic hydrocarbons, evaporate. The lighter ones, such as benzene and toluene, enter the air quickly, whereas the heavier ones, such as napthalenes, persist on the surface. When oil is burned, fewer light hydrocarbons are released into the air than would normally evaporate, according to Kenneth Li of Environment Canada. But those that end up aloft tend to be the heavier, more toxic ones.

Preventing Spills with Hull Design

Tankers could use hydrostatic loading to keep oil from spilling after an accident. The seawater would exert greater pressure than the oil in the tanker.



SOURCE: National Academy of Sciences

If the air pollution trade-off is accepted, burning could get rid of more than 90 percent of an oil slick. "I believe it is the only tool we have that allows you to remove vast quantities at one time," says Mervin F. Fingas of Environment Canada. "And you can eliminate vast shoreline damage." As with all oil-spill technologies, there are limitations. The layer of oil must be more than three millimeters thick, and a noncombustible emulsion of oil and seawater must not have formed. An adequate supply of fireproof booms, barriers that corral the oil, must also be available.

The biggest hurdle currently facing the burning technique in the U.S. is regulatory. The EPA last approved an experimental oil spill in 1979. Experts argue that more controlled spills are needed to evaluate technologies such as in situ burns. "It is very difficult to get someone who's trying to do cleanup to make room for you to do your experiment," says Edward Tennyson of the MMS. MMS recently submitted environmental impact assessments to the EPA requesting two spills of 20,000 gallons off the coast of Louisiana. Tennyson believes the chances of winning approval are 50–50.

For the time being, other countries, such as Canada and Norway, remain the testing ground for many new oil-spill response technologies. "We practice an enormous amount of hypocrisy in this country," comments Teal of WHOI. "We don't control our use of oil; we are one of the biggest consumers of oil in the world. But we do our spill experiments in the waters of other countries."

The key to using both dispersants and burning is speed and prior approval. "If you have the debates after the spill has occurred, you may delay so long that both of these techniques are no longer effective," explains Lindstedt-Siva of ARCO. Both technologies can work if the layer of oil is thick and not widely dispersed from its source. In addition, since booms and skimmers are often in short supply, getting them to the highest concentration of oil could enhance any recovery effort.

In the future, remote-sensing technologies may help locate the thickest regions of a slick. Groups such as Environment Canada, the U.S. Coast Guard and the Marine Spill Response Corporation are studying and testing different detection systems for their potential to spot oil on water.

Several different systems are already in use in the U.S. and Europe. Ultraviolet, or UV, devices can identify oil be-

When Science Is Sealed by the Courts

"Gobbledygook," blusters John S. Oliver, a marine biologist at Moss Landing Marine Laboratories in California. "The reports are crap." Oliver, who traveled to Alaska to study the effects of the *Exxon Valdez* oil spill, is decrying the quality of science being conducted in Prince William Sound. "There is a tremendous amount of coveted data and lawyer-driven data, but most of it has been completely lost to science."

Oliver's concerns are echoed by many scientists. Because of pending lawsuits against Exxon, neither the company nor the federal or state agencies will release detailed information on the extent of the damage to the natural resources. "The normal process of scientific inquiry was set aside," notes John W. Farrington of the Woods Hole Oceanographic Institution.

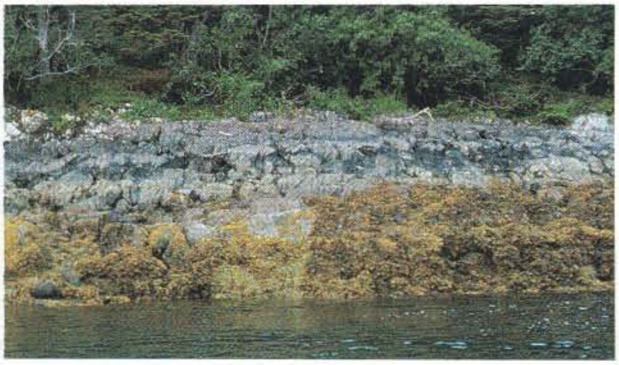
Such secrecy has made it impossible to get a straight reading of recovery (or the lack thereof) and of any sublethal effects of the oil. Some of these findings could have had direct implications for cleanup. Biologist Mark N. Kuwada of the Alaska Department of Fish and Game, for instance, says knowledge about damage to young fish led him to recommend that all oil be removed from some stream beds. At the same time as he encouraged such treatment, however, he could not reveal the studies to support his position.

The lack of specific data on temperature, duration and frequency of hot-water washing at some sites weakens the argument of Jonathan P. Houghton and Dennis C. Lees, contractors working for the National Oceanic and Atmospheric Administration (NOAA). They believe the ecosystem has recovered more rapidly on uncleaned beaches. "Are you sure of the treatment history?" asks NOAA's Gary Shigenaka, as their boat approaches an obvious dividing line running across the rocks in Northwest Bay. "All I am certain of is that something took everything off the rock over there," responds Houghton, pointing to the left, "and not over here."

The scientists' frustration is compounded by the fact that very few studies of the Sound's beaches had been conducted prior to the spill, so there are few standards of comparison in an area of enormous biological diversity. "This Sound characterizes the variability we can find out there," says Jacqueline Michel of Research Planning, Inc., in Columbia, S.C. "Everyone can find data to support his or her position." Researchers who tried to establish controls were often unsuccessful. Houghton and Lees flew around the Sound after the accident collecting data in sites they expected would be polluted. Only one of those sites, however, was oiled.

Long-term studies have also been jeopardized. Pressure to clean the beaches was so great that only 10 or 12 short stretches were set aside to serve as controls. "I worked my butt off to get those going," says David M. Kennedy, director of NOAA's hazardous materials response branch. "It was an incredible fight to get the other [agencies] to agree."

Lawsuits and damage assessment activities are sure to gag research in future oil spills, so scientists are working to ensure that some kind of open exchange can take place despite a litigious atmosphere. The National Academy of Sciences (NAS) is planning a workshop on the problem this fall, says NAS's David Policansky. Conducting good science during such disasters could yield valuable insights about the environmental effects of pollutants such as oil. "Christ, you don't want to create the opportunity," Oliver says. "But, by God, you want to use it when you have it." —*M.H.*



AU NATUREL? Line on the rocks in 1990 may reflect differences between hot-water washing and no treatment.

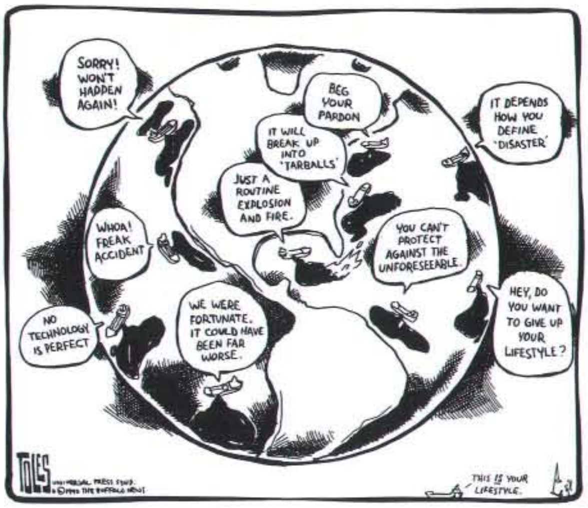
cause it has a higher UV reflectivity than water; consequently, oiled areas appear bright. Unfortunately, UV picks up slicks that are a few millionths of an inch thick as well as wind slicks and sun glints, Fingas says. Infrared systems can discern differences in sea-surface temperature. And oil that is thicker than several thousandths of an inch can sustain a detectable difference in temperature. At night, however, temperatures tend to drop, and the image is altered. Radar is also used, Tennyson says, but it too can be fooled by the incidentals of sea life, such as whale sperm or tuna oil from a killer whale feast. The problem with all of these systems taken together is that "no one can give me thicknesses precisely," says Ronald A. Lambert of the Environmental Research Institute of Michigan. The remote-sensing and imaging technology company has been hired by the Marine Spill Response Corporation to evaluate detection systems that the corporation could purchase.

Another up-and-coming technology is a laser fluorosensor. UV laser light would hit the oil, which would absorb it and fluoresce in the visible spectrum, Lambert explains. The advantage, he adds, is that all kinds of things would fluoresce differently, so a response team could tell oil from algae or anything else floating on the water. Tennyson says the MMS and Environment Canada will soon test a prototypical laser sensor.

Despite their promise, most of these sensing techniques are expensive, not widely available and still unreliable. Human eyes often have to double-check the mechanical vision. The technology "is not fine-tuned enough," comments David M. Kennedy, director of NOAA's hazardous materials response branch, who watched the failure of remote sensing in Prince William Sound. "It has a long way to go, but it is a technology that needs development." Indeed, Kennedy, Tennyson and representatives from the EPA and the coast guard had just finished describing remote-sensing and some other oil-cleanup technologies to a congressional subcommittee this spring, when Congressman Dennis M. Hertel of Michigan brusquely asked what would be changed if the *Exxon Valdez* were wrecked again today. Their answer: essentially not much.

The Oil Pollution Act, first proposed 15 years ago, was finally pushed through last year to prevent a repeat of the confused response to the *Exxon Valdez* and to protect against future spills. But it has had little direct impact to date. Funding to implement the National Contingency Plan, mandated by the act, is on hold, and each agency is waiting for money that has not been appropriated. "We saw the OPA as a savior, so the Commerce Department started phasing out our money. Now we are fighting just for baseline funds," says NOAA's Kennedy, who had trouble hunting down enough cash to continue studies in Prince William Sound.

According to Tennyson, an experimental tank, called the Oil and Hazardous Materials Simulated Environmental Test Tank, sits idle in New Jersey: there appears to be no money to reopen it. The evaluation and improvement of most U.S. oil-spill response technology took place there between 1974 and 1987. Without the use of the facility or controlled spills, most federal research on cleaning up oil spills remains stymied.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WHOA! FREAK ACCIDENT
YOU CAN'T PROTECT AGAINST THE UNFORESEEABLE.
NO TECHNOLOGY IS PERFECT
WE WERE FORTUNATE. IT COULD HAVE BEEN FAR WORSE.
HEY, DO YOU WANT TO GIVE UP YOUR LIFESTYLE?
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THIS IS YOUR LIFESTYLE.

Since the *Exxon Valdez* accident, many companies have presented novel ideas, but technology remains at best a partial solution. "The biggest bang for your buck is prevention," says John S. Farlow, former chief of the EPA's oil-spill engineering research program and self-described grandfather of the tank in New Jersey. "The problem is that it is boring. You need to pay people to wait around day after day for the world to end so they can rush into action." The Oil Pollution Act called for several preventive measures, including training, vessel self-help plans and double-hulled tankers.

Vessel self-help is in its infancy. The intention is to provide each tanker with booms, skimmers or chemical agents, such as dispersants or coagulants, that could contain or treat the oil once it spilled, explains coast guard commander Peter A. Tebeau. But "the question that comes up is: Is the technology feasible?" he says. "Even if it is, do you have enough people on board to do this, will they be properly trained? Will they be able to do this in the event of an accident, or will they be too busy trying to save their own lives and the vessel?"

A better-known approach to prevention, the double-hulled tanker, would place a protective space between the outside wall of the vessel and the inner wall of the oil storage tank. Under the Oil Pollution Act, these tankers are slowly being phased in, and it is expected that by 2015, all tankers in U.S. waters would be so designed. Indeed, the International Maritime Organization (IMO) is considering whether to recommend that all tankers be equipped with double hulls or some other protective design. (Eighty percent of the tankers in U.S. waters are foreign owned.)

As a recent NAS review of 17 tanker designs stated, however, double hulls offer only a partial solution. For high-impact collisions, such as the *Exxon Valdez,* they would not be as effective as other designs. And volatile hydrocarbons may accumulate between the hulls, increasing the risk of an explosion. Because no one blueprint can address all safety concerns, NAS also recommended incorporating hydrostatic loading into tanker design. This concept, which has not yet been integrated into a seafaring tanker, is also being reviewed by the IMO. The idea is to reduce the level of oil in the vessel so that water pressure from the surrounding ocean will contain the oil in the case of a rupture.

Tanker Cowboys

Tankers could also divide the storage of oil between an upper and a lower deck, a design called intermediate deck. In the event of an accident, the hope is that only one tank would be damaged. "You might consider intermediate decks on big tankers, which are more likely to have high-energy ruptures, and double hulls on smaller ships, which are more likely to have low-energy collisions," suggests Henry S. Marcus, chairman of the Oceans Systems Management Program at the Massachusetts Institute of Technology, who chaired the NAS review.

One problem of the Oil Pollution Act with regard to tankers is liability. Although limits in damages are mandated by the act, some experts say there are so many exception clauses that no tanker operator can envision an accident where such limits would apply. That means that it may be too costly to enter U.S. waters. "We are concerned that the legislation will discourage reputable tankers from traveling to the states," says Neil Challis, a technical adviser to the International Tanker Owners Pollution Federation, a London-based organization. "Instead you'll get tanker cowboys—and perhaps more spills."

The guiding principle of prevention, if sustained, could also apply to smaller, less publicized accidents. During 1988, for example, some 16,000 spills dumped more than four times the amount of the *Exxon Valdez* spill into U.S. waters, according to a recent report by the General Accounting Office. Indeed, a 1985 NAS study estimated that 33 percent of the oil entering the seas each year comes from normal tanker operations, such as ballast release, and 36 percent comes from industrial and urban runoff. Plugging these leaks is as pivotal as preventing tanker accidents.

No unifying cleanup ethic has emerged from Prince William Sound. On one beach, Kuwada watches as an Exxon crew removes oil-soiled rocks and prepares to spray Inipol. Pointing to a salmon stream, he says, only half seriously, "You're not going to get your Inipol in there." An Exxon scientist steers clear of the comment. Soon the stench of Inipol fills the air. The next day, on another beach, Kuwada and other state workers weigh the merit of backhoeing an upper section of beach and disrupting the beach grass growing there. They agree to ask Exxon to return with the heavy equipment. A week later to the north, on yet another beach, Houghton and his team celebrate an abundance of young sea urchins (uncommon in an area usually ransacked by otters), mussels, tiny fish called gunnels and clams: "This is what happens when you don't treat."

Even during this third and apparently last summer of Exxon cleanup, disagreements about treatment are common. "It's another episode of *As the Sound Turns,*" one beach worker jokes.

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The Light Fantastic

Graphics researchers polish their images

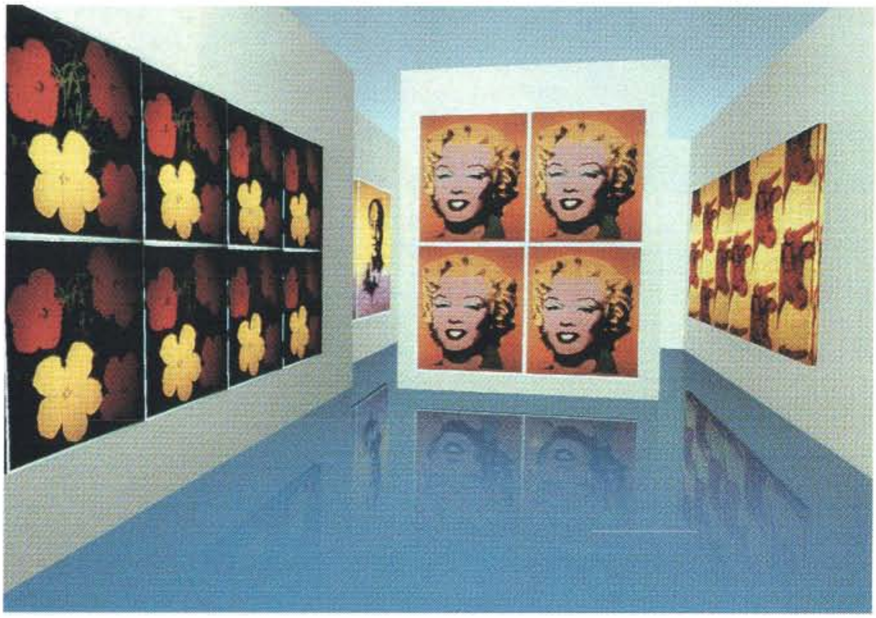
Computer-generated images of sunbeams streaming through chapel windows or of a gleaming robot bent on terminating its target seem compellingly real. But the computer scientists and mathematicians who try to transfer the geometry and light of the real world onto the two-dimensional glass palette of a video display keenly understand the artifice involved in their creations. "Ninety to 95 percent of the pictures you see as photographs can't be simulated on a computer screen," exclaims Patrick M. Hanrahan of Princeton University's department of computer science.

Achieving true photorealism—an image as simple and difficult to depict as blades of grass rippling in a breeze—is important. Advances in the field will affect design of next-generation automobiles, architectural models and maybe even the special effects for the next Arnold Schwarzenegger movie.

Borrowing ideas from the physical and biological sciences as a means to attain lifelike fidelity has been a recurring theme in recent years of the annual meeting of the Special Interest Group on Computer Graphics of the Association for Computing Machinery, which regularly draws about 25,000 people. At the conference held this summer, the graphics community gave belated recognition to the wave nature of light and demonstrated how principles from biology can be applied to building and texturing graphics images.

A group from Cornell University's program of computer graphics—Xiao D. He, Kenneth E. Torrance, François X. Sillion and Donald P. Greenberg—claimed credit for the first graphics model of light reflection based on wave optics. Light-reflection models, which are required by graphics programmers to calculate the color and shading of surfaces, have until now used geometric optics, which picture light as rays instead of waves.

But modeling light as a pattern of straight lines makes it impossible to simulate diffraction and polarization. So a surface must be depicted as either perfectly diffuse (reflecting equally in all directions like a carpet) or mirrorlike (reflecting light in only one direction). Only imperfect calculations can be made for reflections from surfaces that may combine both properties.



***WAVE OPTICS** was used in a Cornell University light-reflection model to help depict how a floor becomes gradually more mirrorlike as the viewing angle changes.*

The Cornell reflection model, Torrance predicts, may make it possible to establish for the first time a nearly comprehensive data base of how materials reflect light. An automobile designer would only have to specify surface roughness and the desired type of paint or aluminum to create an accurate simulation of how light bounces from the hood of a new car. The work may also mark the first time that a graphics model's predictions have been compared with measurements of the way light actually reflected from a material, Torrance notes.

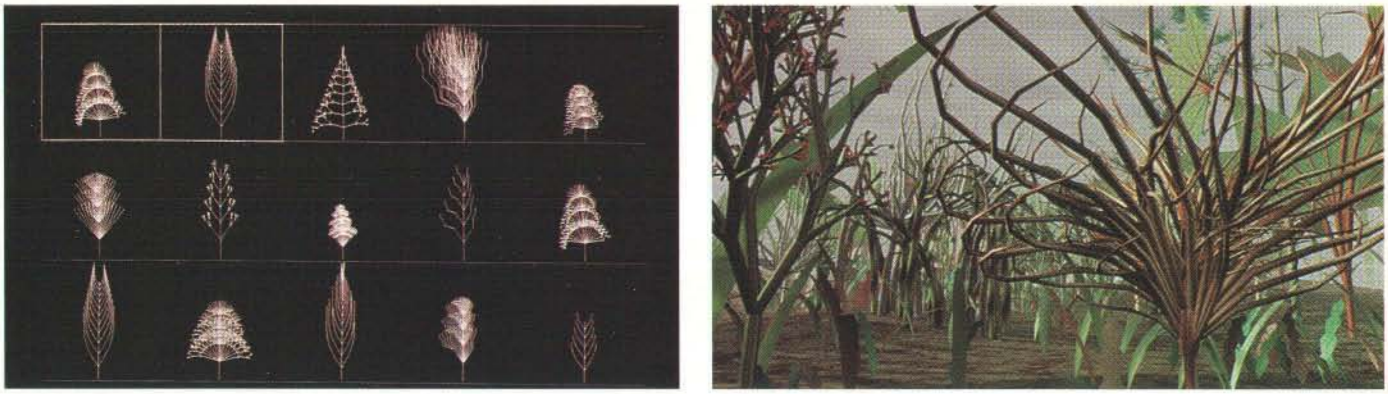
Knowing how light reflects off a surface is only a part of rendering an image. The designer must also use an algorithm that tracks the path of light as it bounces from surface to surface. In another paper, Cornell researchers describe an interreflection algorithm that makes use of their light-reflection model to display a continuum of images from specular to diffuse. Greenberg hopes this work will supplant two of the most widely used interreflection algorithms: ray tracing for specular surfaces and radiosity for diffuse surfaces.

Greenberg's wish will be realized only if the complexity of this algorithm can be tamed. Currently it consumes massive amounts of computer processing time. The new method takes several hours on a high-powered workstation to construct the shading and coloring for a single image.

A similarly detailed approach is required for the laborious construction of a three-dimensional model of an object, which is often made as a mesh of thousands of tiny polygons. A designer specifies how these intricate skeletons move. The model is then colored and shaded using algorithms and models such as those worked out by the Cornell researchers. Still other algorithms provide texturing of the model's surface.

One of the most challenging problems in this long process is how to generate natural shapes and patterns. Graphics researchers have looked to biology for help.

Using one image as the progenitor of another—a process called artificial evolution—was the technique employed to create a short film entitled *Panspermia.* The film chronicles the landing of spores on a barren planet, the subsequent development of these spores into lush vegetation and, finally, the launching of pods of new spores into space,



***ARTIFICIAL EVOLUTION** proceeds by mating different plantlike structures* **(boxes in upper left photo)** *to make varied offspring, which were colored and arranged to produce* **Panspermia,** *a computer graphics film* **(center).** *Andrew P. Witkin used reaction-dif-*

where they presumably traveled to germinate on other worlds.

Karl Sims, a researcher at Thinking Machines Corporation in Cambridge, Mass., evolved his plants from a set of 21 parameters, a genotype that codes for plantlike structures and growth characteristics. He then set about to generate a mutant gene pool by using an algorithm that randomly varied the parameter values. The genes were then subjected to further mutations, or in some cases two genotypes were mated.

At each step, Sims inspected the phenotypes—the actual plant forms created from mutating or mating genotypes—and decided which, if any, of the offspring in each generation should survive. Through such weeding out, he was able to "cultivate" tropical vegetation, which was then assembled as the imagery of the final two-minute film. Sims has since refined the technique by randomly changing the equations that are used for controlling the growth process.

Artificial evolution is related to a subdiscipline of computer science, known as artificial life, that uses what are called genetic algorithms to evolve codes; these codes can be used to depict images or help machines teach themselves. Devotees of artificial life specify an overall objective—telling an ant to negotiate a maze, for example—and then let the algorithm figure out the best way to achieve that goal. But only Sims and a few other researchers stop the process at each step, which gives them a measure of aesthetic control over the evolutionary process. "It's survival of the prettiest," he says.

A model that the mathematician Alan M. Turing thought might explain pattern formation in nature is also finding application in computer graphics research. Turing hypothesized that the movement and interaction of different chemical messengers throughout the embryo—substances he called morphogens—might trigger cells to express

Don't Change the Channel, Rearrange that Face

If you don't like what you are seeing on television, someday you may be able to do more about it than resorting to the "zapper." Multimedia technology will allow the user of a personal computer to combine standard text and graphics with video, audio and animation. Merging any of these media may eventually be as easy as moving a paragraph in a word-processing software package.

Before any of this happens, though, computer and electronic manufacturers must convince people to buy multimedia systems. Although the technology has been billed as a revolutionary new medium for business, education and the home, its cost and the need to assemble a complete system from scratch has until now prevented the young technology from achieving wide acceptance. Definitions of multimedia vary. Many systems attach a compact-disc player to some form of computer microprocessor and display monitor. These products may range from a personal computer to a television set hooked to a device that resembles a videocassette recorder.

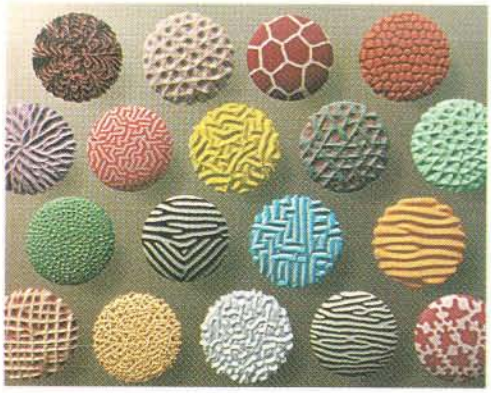
Leading computer and electronics companies are addressing the marketing and technical barriers to foster broad endorsement of the technology. In early October, Microsoft, the Redmond, Wash., software company, and a legion of other companies—12 hardware suppliers, including Tandy, AT&T Computer Systems, Fujitsu and NEC Technologies, as well as more than 40 electronic disc publishers—are expected to demonstrate a battery of multimedia products. The electronic titles will range from encyclopedias to games. A multimedia dictionary, for example, not only might spell onomatopoeia but pronounce it as well.

The products will be compatible with Microsoft's popular Windows software, which allows several programs to be run simultaneously. Microsoft is also trying to position itself as a major publisher of multimedia titles on specialized compact discs called compact-disc read-only memory (CD-ROM). It will be introducing its own discs along with those of other publishers. And the company has purchased a stake in Dorling Kindersley, a British publisher of reference works.

Microsoft has worked closely with other companies to develop what it hopes will become a technical standard for the products being released, each of which will bear the label "MPC" for multimedia personal computer.

Although Microsoft and its partners set a goal of making these products affordable to home purchasers, the most inexpensive hardware will still cost at least $2,500—or $800 to add a CD-ROM player and an audio circuit board to an existing personal computer. The discs themselves will sell for a minimum of $50, ranging up to several hundred dollars.

In the home market, MPC products may compete for some uses against more inexpensive multimedia hardware from Philips Consumer Electronics and



fusion, a biologically influenced model, to yield natural patterns and textures **(right).**

a pigment or develop into the contours of a texture. The original model for what Turing called reaction-diffusion can be described by a series of nonlinear partial differential equations that developmental biologists have used to postulate how butterfly markings, leopard spots or other patterns may be formed.

For graphics, the concentrations of each "chemical" computed by the equations can be translated into the value of a picture element and used to help shade an image. Reaction-diffusion is an addition to other models, such as fractals, that can be used to achieve naturalistic effects.

Researchers hope their work may eventually be adopted by biologists as a technique for simulating pattern formation. The reasons are evident. Andrew P. Witkin of Carnegie Mellon University cut out a patch from a photograph of a fingerprint and then used reaction-diffusion to regrow the missing whorls. "Developmental biologists don't know how patterns form in real animals," Witkin says. "The visual resemblance between the variety of patterns we make and the variety of patterns we observe is complex. I think all we can say is there is compelling visual evidence that there may be a connection here."

Perhaps the most difficult challenge in achieving physical realism is to make graphics figures seem to move naturally. Although the best Hollywood animators are already able to create lifelike motion, many of the characters generated by computer graphics still move stiltedly from one position to another.

Marc H. Raibert of the Massachusetts Institute of Technology Leg Laboratory and Jessica K. Hodgins of the IBM Thomas J. Watson Research Center have developed a control system that can instruct one-legged kangaroos, two- or four-legged robots and other creatures to run, trot, gallop or hop. By specifying the path and gait that the kangaroo takes, the animator acts more like a film director of these creatures than a craftsman preoccupied with the movement of each joint.

The control system takes this specification and instructs a kangaroo how fast to move and how to stay balanced so it does not fall on its snout. At the same time, a model ensures that the applied forces on the joints result in physically correct motion. Slavish adherence to physical laws may or may not be what an animator intended. "The machines have a mind of their own," Raibert says. "They want to move in some ways and not in others."

Raibert and Hodgins's interest in graphics stems from work on robotic motion at the M.I.T. Leg Laboratory and elsewhere. The two researchers adopted computer animation techniques as a means of simulating how robots move before they are built. Now they want to pursue graphics research for its own sake. A fully animated kangaroo—and one with two legs—is grist for another conference, though. "These kangaroos don't carry babies in their pouch, pick bugs off their fur or bend over and drink water. All they do is run and jump when you tell them," Raibert says. A two-legged human with a convincing gait is still a distant prospect. *—Gary Stix*

Commodore, devices that attach to a television and stereo and sell for under $1,000.

In the business and education markets, these products may also face a competitive challenge. One reason that Apple Computer and IBM recently agreed to develop technology jointly was because of their interest in multimedia. Another reason was their apparent desire to combat Microsoft's dominance in the software market.

It may be years before the various media fully merge: enormous amounts of data must be compressed onto a disc, and many systems still have trouble displaying video. But interest in multimedia continues to grow. And schools throughout the state of Florida have begun to outfit themselves with multimedia systems. Schoolchildren there might be able to watch a multimedia presentation of an airplane as it breaks through the sound barrier—or they might practice editing a video magazine. *—Gary Stix*

Secret Garden

Cell culture may provide a unique route to taxol

It takes 100 years or more for the trunk of a Pacific yew tree, *Taxus brevifolia,* to achieve a girth of just nine inches. That is a long time to wait for a bit of bark. And yet the woody covering of this relatively rare species is at present the only source of taxol, a drug that is showing marked success as a treatment for ovarian cancer.

Widely anticipated to prove effective in treating other cancers as well, taxol could be a blockbuster drug—but only when and if it can be produced in greater quantity. Unfortunately, the compound is so complex that most drugmakers despair of ever being able to synthesize it chemically. So some scientists are attempting to take another route. They hope to obtain taxol from cultures of individual yew cells.

Plant cell culture has much in common with fermentation techniques used in the biotechnology industry to produce proteins such as insulin. Yet "the basic groundwork has never been laid for plants the way it has been for bacteria and mammalian cells," declares Michael L. Shuler, professor of chemical engineering at Cornell University. "There has never been an agency like the National Institutes of Health to do the research," he points out.

Now the National Cancer Institute is trying to make up for lost time. In August the agency awarded Shuler and a five-member research consortium under his direction a $1.27-million grant to develop techniques and equipment for large-scale production of taxol via plant-cell tissue culture. The participants include the chemical engineering departments at Cornell and at Colorado State University, the U.S. Department of Agriculture's Agricultural Research Service (ARS) plant protection research unit, Hauser Chemical Research in Boulder, Colo., and Phyton Catalytic, a plant biotechnology company based in Ithaca, N.Y.

Shuler predicts that a workable large-scale tissue culture system for taxol will be developed within two to four years; within five years, companies could be producing kilogram quantities of taxol. Some 50 kilograms of this potent drug would probably suffice to treat all 12,500 cases of ovarian cancer diagnosed in the U.S. each year. Much larger quantities will be needed to satisfy worldwide demand if tests show that the drug is also effective against other cancers.

Many technological hurdles must be

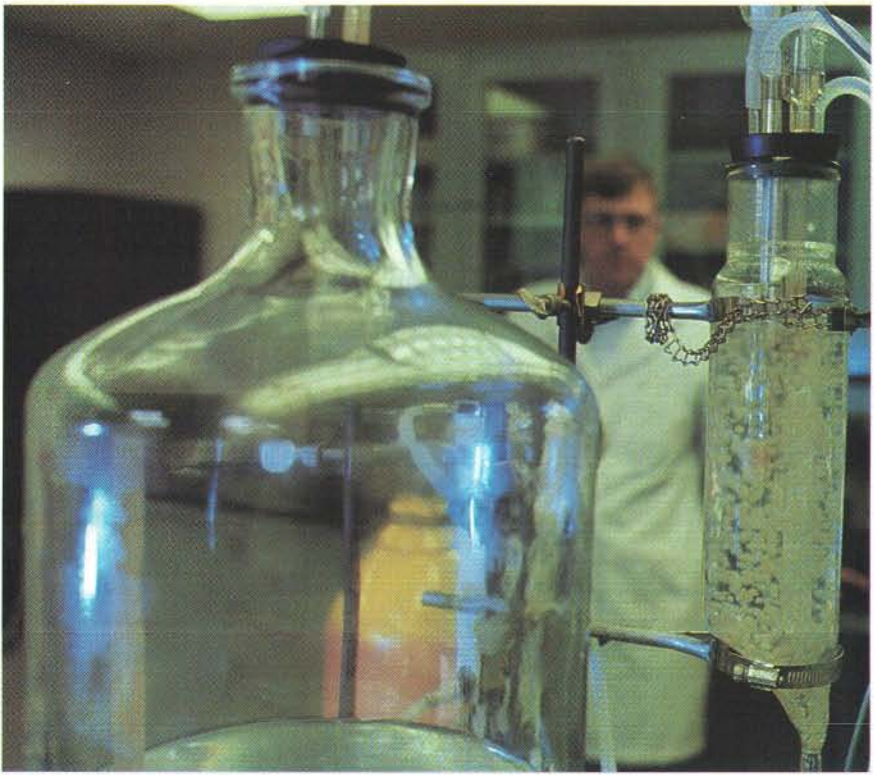
overcome before trees can be grown by the tankful. Because the Pacific yew is not a commercial tree like oak or walnut, almost nothing is known about its biology, notes Donna Gibson, a plant geneticist at the ARS in Ithaca and one of the inventors of taxol production from tissue culture. Her laboratory team is investigating how environment and genetics affect the amount of taxol a given yew tree produces. Sun and shade, the age of the tree and its gender may be influential. The area of the tree from which cells are taken may prove most important, Gibson declares, noting that the consortium will focus its efforts on root tissue rather than bark. "Once we've got a handle on the cell lines, we'll look for the optimum ways to alter the environment," she says.

The researchers will then attempt to increase taxol production even further. One way involves challenging the cells with natural enemies, such as fungus. The plant cells respond to this stress by producing more of certain metabolites. Yet the pathogens that provoke the biggest response from yews in nature may not be the most significant in production vats, or bioreactors. "We will try an array of potential elicitor compounds," Shuler says.

The things that stimulate production and those that stimulate growth are often mutually exclusive, so part of the process of bioreactor design is gauging when to introduce certain nutrients and shut off others. In addition, one of the most dramatic influences on plant cell productivity is caused by the physical arrangement of cells inside the bioreactor. Instead of merely floating free in the tank, cells are immobilized, either by membranes or beads of foam or glass to maximize their productivity.

Feedback and inhibition loops like the ones that regulate the production of human hormones operate in plants, too; they stimulate or call a halt to manufacture of certain compounds when a preordained level is reached. To take advantage of this mechanism, researchers are looking for a way to remove taxol from the fermenter continuously. In one such method, known as in situ absorption, the desired compound is captured by a porous resin as it is produced, so the cells are stimulated to manufacture even more.

Any advance in extraction technology would be a welcome improvement over the complex, laborious process necessary to remove from dry bark just 0.01 to 0.03 percent of taxol. "The way we do it now is like carving a statue—you have to know what you want and remove everything you don't," sighs David T. Bailey, manager of natural products research at Hauser Chemical, which performs the task for Bristol-Myers Squibb. "We hope the tissue culture guys will come up with a system that won't have so many molecules that are tough to remove," he says.



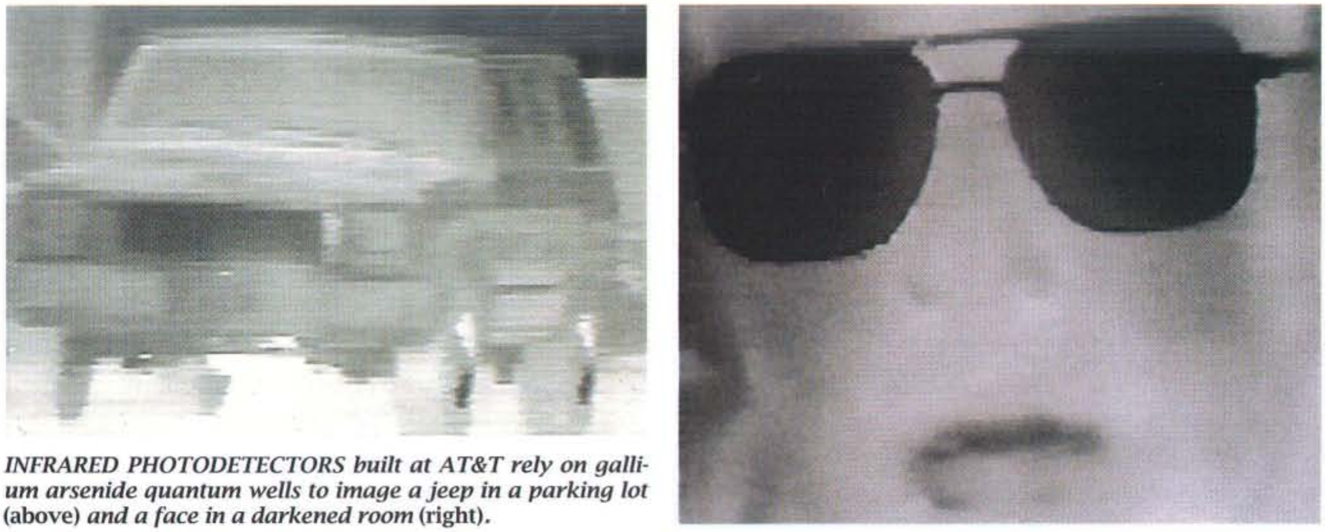
PLANT CELL BIOREACTOR, like the laboratory-scale model developed by Michael L. Shuler of Cornell University, may enable Pacific yew tree cells to yield the anticancer drug taxol. Photo: Jason Goltz.

Among those molecules are other compounds structurally similar to taxol, called taxanes. Bailey is not alone in hoping researchers develop a number of cell lines, each capable of producing a particular taxane in abundance. With deft chemistry, these taxanes might serve as precursors for taxol. That possibility has not escaped the attention of Bristol-Myers Squibb, which like other pharmaceutical companies is more comfortable with chemical synthesis and its economies of scale. Bristol-Myers Squibb currently extracts the drug from bark and is funding research to obtain it from needles.

Performing partial synthesis on taxanes might well be cheaper than making taxol proper, but not if the only source is a dwindling supply of living trees. So there is incentive to develop plant-cell tissue culture systems for the *Taxus* species even if the ultimate goal is not pure taxol. In addition to serving as precursors, some taxanes might prove even more effective than taxol against certain types of cancers.

The competition surrounding taxol is already getting nasty. Congressional hearings were held in late July at the request of Representative Ron Wyden of Oregon. His ire has been sparked by the U.S. Forest Service and the U.S. Bureau of Land Management. Those bureaus effectively shut out northwestern companies, he asserts, by agreeing to give Bristol-Myers Squibb exclusive access to some 23 million trees on eight million acres of national land. To further complicate matters, the only U.S. patent to be issued on production of taxol via tissue culture belongs to the ARS, the research arm of the USDA; it has licensed that patent to Phyton Catalytic. Meanwhile Escagenetics in San Carlos, Calif., is pursuing the method.

While the turf battles are brewing, plant-cell culture technology is too. That is good news even for companies that lose this round and for those that previously dismissed the technology in favor of conventional chemical synthesis. Shuler points out that a wealth of chemical diversity in the plant kingdom—especially in slow-growing woody plants—goes untapped in part because no technology exists to ensure that if something useful were found, it could be made in large quantity. If the cell culture method of producing taxol is successful, it may well open the door to a secret garden of botanical drugs. —*Deborah Erickson*



***INFRARED PHOTODETECTORS** built at AT&T rely on gallium arsenide quantum wells to image a jeep in a parking lot* **(above)** *and a face in a darkened room* **(right)**.

Body Heat

QWIPs offer a new way to see in the dark

As the videotape runs, the ghostly figure of a man stares out at the camera. He flexes his fingers, then picks up a soda can and presses its top to his cheek, where it leaves a shadowy image. In another tape, an inflamed blood vessel throbs beneath the skin of a woman's face.

For the past few months, researchers at Bell Laboratories in Murray Hill, N.J., have been shooting a curious collection of videos. Some have been recorded in total darkness; others picture phenomena invisible to the unaided eye. These videos are portraying infinitesimal differences in infrared radiation—in essence, temperature. Key to these cinematographic undertakings are arrays of quantum-well infrared photodetectors (QWIPs).

The military has long been a fan of infrared detection, more picturesquely called night vision. M-1 tanks and Apache helicopters rely on such imaging systems to pick their way through dark or obscured landscapes. Reconnaissance satellites peek through cloud cover with the help of infrared detectors.

Such night vision sensors generally rely on an uncommon compound semiconductor material, mercury cadmium telluride, or "mer-cad." Most terrestrial night vision systems sense in two windows of radiation: wavelengths that range between three and five microns and those between eight to 12 microns.

"People generate infrared radiation all the time," particularly in the five- to 10-micron range, points out Clyde G. Bethea, a researcher at Bell Labs. On the other hand, because water absorbs five-micron radiation, only those detectors sensitive to longer wavelengths can "see through" a rainstorm. "So if the planes attacking Iraq had had 10-micron detectors, they wouldn't have been held up by the weather," Bethea adds.

Unfortunately, mer-cad is an unruly material to process especially when it is pushed to respond to longer wavelengths. The Defense Advanced Research Projects Agency is funding an ongoing program to improve the manufacturability of the material.

Enter gallium arsenide. After decades of work, researchers have honed techniques for making gallium arsenide crystals that approach atomic perfection. Then, four years ago, Bethea and his colleague Barry Levine realized they could use their methods for making gallium arsenide optical switches to build infrared detectors. "People kept saying it couldn't be done," Bethea says. "They just had the physics all wrong."

The researchers employed a quantum well—a sliver of a semiconductor riddled with low-energy electrons sandwiched between slightly different semiconductor layers that contain higher-energy electrons. Because they can precisely control the flow of electrons through a quantum well, workers can custom-design the electronic and optical properties of such materials.

The first detector array Bethea and his colleague Vera O. Shea built had only 10 picture elements, or pixels, but it offered enough proof to attract the attention of AT&T's development arm. Over the past two years, the researchers have teamed with development engineers to build arrays with more than 16,000 pixels. The detectors are sensitive to temperature differences as small as ten-thousandths of a degree. The cooler the object, the darker its image.

The military is the most voracious consumer of infrared detectors, but AT&T is eyeing the commercial markets as well. "Power companies love these things because you can shine them on poles and see that one transformer is hotter than another," says William A. Gault, who supervises work on optoelectronic devices at Bell Labs.

AT&T nonetheless faces several challenges before its infrared photodetectors win converts. Like mer-cad, the gallium arsenide devices must be cooled to low temperatures. Designing the entire recording system to operate at the same temperature is not easy. Still, Gault hopes to raise the system operating temperature from below 70 kelvins to 80 kelvins by late next spring. Bethea and Levine are also working to increase the number of pixels in their array and to boost the effectiveness of their systems.

An even tougher challenge may be that of breaking into the military market for infrared detectors. Mer-cad devices are already in production, notes John Pollard, acting deputy director of the infrared technology division at the Army Center for Night Vision and ElectroOptics; gallium arsenide quantum-well photodetectors are not. "At the present time, mer-cad will outperform the quantum wells available," he adds.

The AT&T researchers are determined to gain ground. Corporate management is putting increasing pressure on the research laboratory to produce new products. "We're more entrepreneurial than we were in the past," Gault declares. His group aims to nurture the nascent detectors through the entire development life cycle.

"We have our *hoshin* goals," Gault says, grand objectives that just border what is possible. On the top of his list: "Making all the detectors in the world out of QWIPs." *—Elizabeth Corcoran*

How's My Driving?

Trucking companies look over their drivers' shoulders

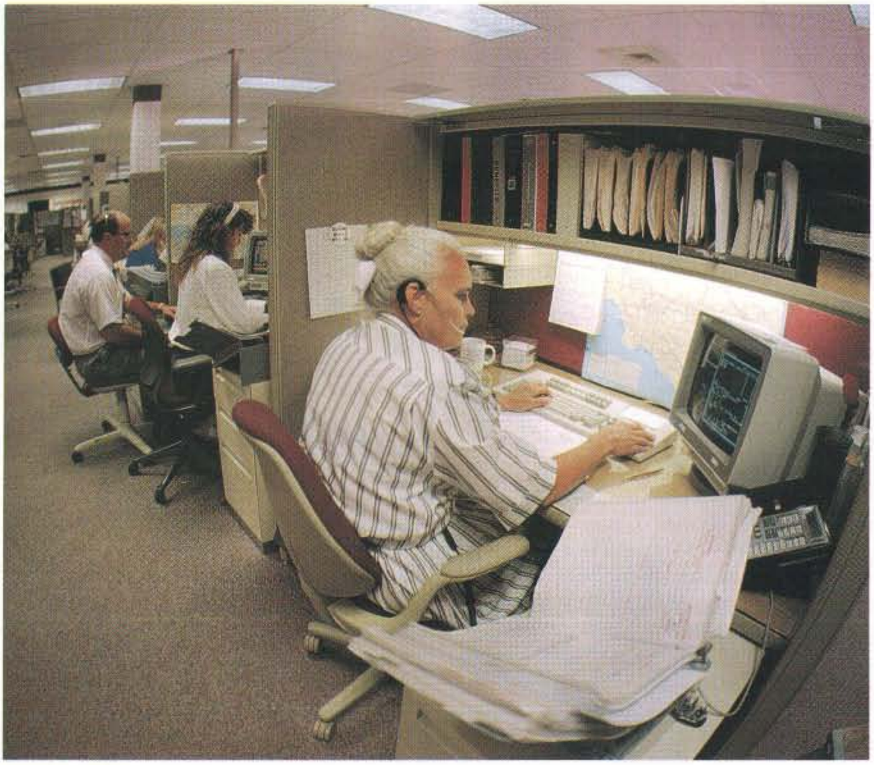
Fleet owners already know where their trucks are. Many have installed tracking systems that relay vehicle location and messages by satellite or mobile radio from a truck to a central dispatching station. Now refinements to this form of remote tracking may soon let fleet owners actually look over their drivers' shoulders from afar—and even second-guess them when necessary. "If a driver is speeding down a hill in neutral, the dispatcher can radio him to knock it off," says Timothy D. McCarthy, a Motorola marketing manager.

At the American Trucking Associations (ATA) meeting this month, Motorola and Qualcomm, Inc., its main competitor in the rapidly growing truck-tracking market, plan to announce a series of products that give an instant picture of a driver's performance and an engine's state. This is accomplished by linking their communications systems to an electronic module called a trip recorder. (Motorola transmits voice and data over a terrestrial radio link; Qualcomm transmits data over a satellite system.)

Trip recorders, which have been on the road for a decade, are the equivalent of aircraft black boxes. They monitor miles traveled and vehicle speed and can sometimes record a truck's behavior during an accident. By tying the device into these networks, the vehicle dispatcher can virtually peer at the odometer and speedometer readings in the truck cab.

The communications equipment can also be connected to electronic engine diagnostic systems sold by manufacturers of truck engines. Diagnostic data on engine timing or fuel injection—information that may not be available to the driver—can be transferred to a waiting maintenance crew. A similar link to sensors that monitor cargo can detect rising temperatures in a refrigerated trailer. As sensors improve, a depot may be instantly alerted to escaping vapors or a fire.

Improved monitoring will provide the fleet owner with a detailed picture of equipment health and driver performance for an entire fleet, enabling split-second rescheduling decisions. "Now you will know not only what the driver said was the problem but what the computer told you was the problem," says Guy T. Rini, section manager of electronic products at Mack Trucks. "You can't afford to make operational mistakes by finding out six hours too late that all you needed to do was bring out five gallons of fuel."



FLEET DISPATCHERS at Schneider National, Inc., track the location and operation of the company's truck on a satellite monitoring system. They can even tell if a driver has been speeding or idling the engine too much. Photo: Jerry Turba.

The system benefits for drivers, many of whom are paid by the mile, translate into reduced time spent waiting to find out where to pick up the next load. But drivers may be less enamored than their bosses with electronic leashes. "The reaction of drivers to trip recorders hasn't been too favorable," says R. V. Durham, freight director for the International Brotherhood of Teamsters. "One of the things that makes the driving job attractive is that there is a certain amount of independence on the road." Durham says trip recorders tend to be used by some nonunion long-haul freight carriers, whose operators have less professional experience than their union counterparts.

Yet some fleets have incentive programs that give drivers bonuses for staying within limits imposed by a trip recorder. Burns Motor Freight, a small fleet based in Marlinton, W. Va., gives drivers up to $3,000 a year for remaining within specified speed and idling restrictions. "I tell the drivers I can send a check to Exxon, or I can send it to you," says Fred C. Burns, Jr., the company's president.

Further refinements will make truck dispatching even more like mission control. Qualcomm is planning to introduce software at the ATA meeting that will fuse truck position data with a mathematical scheduling algorithm to determine optimal fleet routing. Motorola plans to introduce a facsimile machine for truck cabs later this year that can be used to receive state trucking permits.

There may be a legal limit on the pace of automation, however. Customers are asking whether they can issue a command that can control driving speeds or shut the truck down. Philip Jenquin, Qualcomm's director of marketing, has refused all such requests because of the liability issues. "If you've got somebody in a wheelchair, whoever is brought into a court is going to pay," Jenquin says.

By and large, the outlook for these systems seems good. Qualcomm, the market leader, has 140 customers and has sold more than 17,000 units for its satellite communications units, each of which costs about $4,500. And fleet owners' desire to know as much as possible about a journey may yield even more information about a driver's perception and state of mind. Research proposals call for examining sensor systems to identify obstructions in the road or monitor driver physiology to detect drowsiness. *—Gary Stix*

THE ANALYTICAL ECONOMIST

An Illusion of Economic Stability?

For all the endless whipsaw of recession and inflation that plagues the modern economy, policymakers and academics alike take comfort in the thought that things used to be far worse. Today's fluctuations are less than half the magnitude of their predecessors, according to the prevailing orthodoxy. The panics of 1907 and 1893, when economic activity came to a near standstill for months at a time, are ancient history. And even more important, manipulation of the business cycle has staved off a repeat of the Great Depression.

A band of younger economists has been reexamining the numbers on which this good news is based. They contend that the picture of increased economic stability since World War II is nothing but a statistical mirage.

The revisionist ringleader is 32-year-old Christina D. Romer of the University of California at Berkeley, who maintains that earlier economists used faulty techniques to estimate the volatility of the prewar economy. Her calculations indicate an improvement in stability that ranges from insignificant at worst to marginal at best. The old guard disagrees, of course, either disputing the validity of Romer's work or contending that even slight improvements in economic stability are important.

The heart of the problem is that before the 1940s no one routinely recorded data on gross national product, national unemployment rates, consumer price indexes or other sweeping economic indicators. Economic historians have been forced to reconstruct these measures from the sparser numbers that were kept, mostly production figures for such basic commodities as wheat, corn and pig iron.

Today the production of goods (as opposed to transportation, building or services) accounts for only about a third of GNP. The early reconstructions hinged on the assumption that the rest of the economy mirrored precisely the swings in mining, agriculture and manufacturing. This assumption is patently false today: the rest of the economy moves on a much calmer course than does commodity production.

Romer extrapolated the current relation between commodities and GNP back to the prewar data and found that recessions and expansions during the late 19th and early 20th centuries were not twice as strong as their postwar counterparts. Instead they were perhaps 25 percent stronger, hardly a major difference.

When Romer and her cohorts extended the work on GNP to analyses of such bellwethers as unemployment and stock prices, they found that their volatility had been exaggerated as well. Take unemployment, for example: earlier economists neglected the fact that the labor force (those people either employed or actively looking for work) increases during economic expansions and decreases during recessions. As a result, past estimates of the number of unemployed as a percentage of the labor force fluctuated more sharply than do modern figures. Steven M. Sheffrin of the University of California at Davis has also looked at GNP for other industrialized nations: except for Sweden, their GNPs too have not become significantly more stable over time.

Have the past 50 years of cigars and pipes in the boardroom of the Federal Reserve led only to so much smoke?

Leading the counterattack is Robert J. Gordon, age 51, a professor at Northwestern University. Gordon faults Romer for applying postwar models of the economy to prewar data, saying that Romer is in effect presuming the phenomena she proposes to measure. He claims that the prewar economy was heavily based on production and that consequently other sectors did move in lockstep with commodities.

Gordon also brings additional data to the fray, in the form of figures for construction and transportation. According to his numbers, both sectors were highly volatile during the late 19th century, and he argues that Romer paints a falsely quiescent picture by ignoring them.

Romer and others, of course, are not convinced by Gordon's work. Jeffrey A. Miron of Boston University points out that the behavior of indicators other than GNP appears to support Romer's position. "Gordon has only done GNP," he says. "Christie's case is on firmer, broader ground."

Although Gordon denies the charge, Miron argues that a significant part of Gordon's newfound volatility in the old numbers comes not from including transportation and construction but from his choice of a particular price index to convert nominal dollar figures to "real" GNP. The index in question was intended to convert consumer prices from current to constant terms, but Gordon uses it to adjust commodity prices instead. According to Gordon's published data, the choice of index could account for almost half of the difference between his figures and Romer's.

There is no clear consensus on who is right. And regardless of who carries the current debate, the old mainstream dogma of a stabilized modern economy is in trouble. Although Romer and Gordon differ, says J. Bradford De Long of Harvard University, their views are much closer to each other's than either one is to the view of the past that economists treasured as recently as five years ago.

Does that mean the past 50 years of cigars and pipes in the boardroom of the Federal Reserve have led only to so much smoke? Even Romer isn't willing to go that far. Instead she and others suggest that the Fed has had priorities other than reducing the variance of GNP on its agenda. Indeed, on a number of occasions the Fed has deliberately engineered recessions to counter the even worse bugaboo of inflation.

De Long also notes that the commonly held belief in a transition from a laissez-faire economy to a managed one may be as illusory as the mainstream gospel of increasing stability. During the panic of 1907, for example, the heads of the major New York banks took counsel in J. P. Morgan's living room, pledged themselves to easy loans and increased the money supply by 10 percent. The difference between the prewar and postwar eras, De Long says, is not so much how stable the economy has been, but who manages it and for what purposes.

—Paul Wallich and Elizabeth Corcoran

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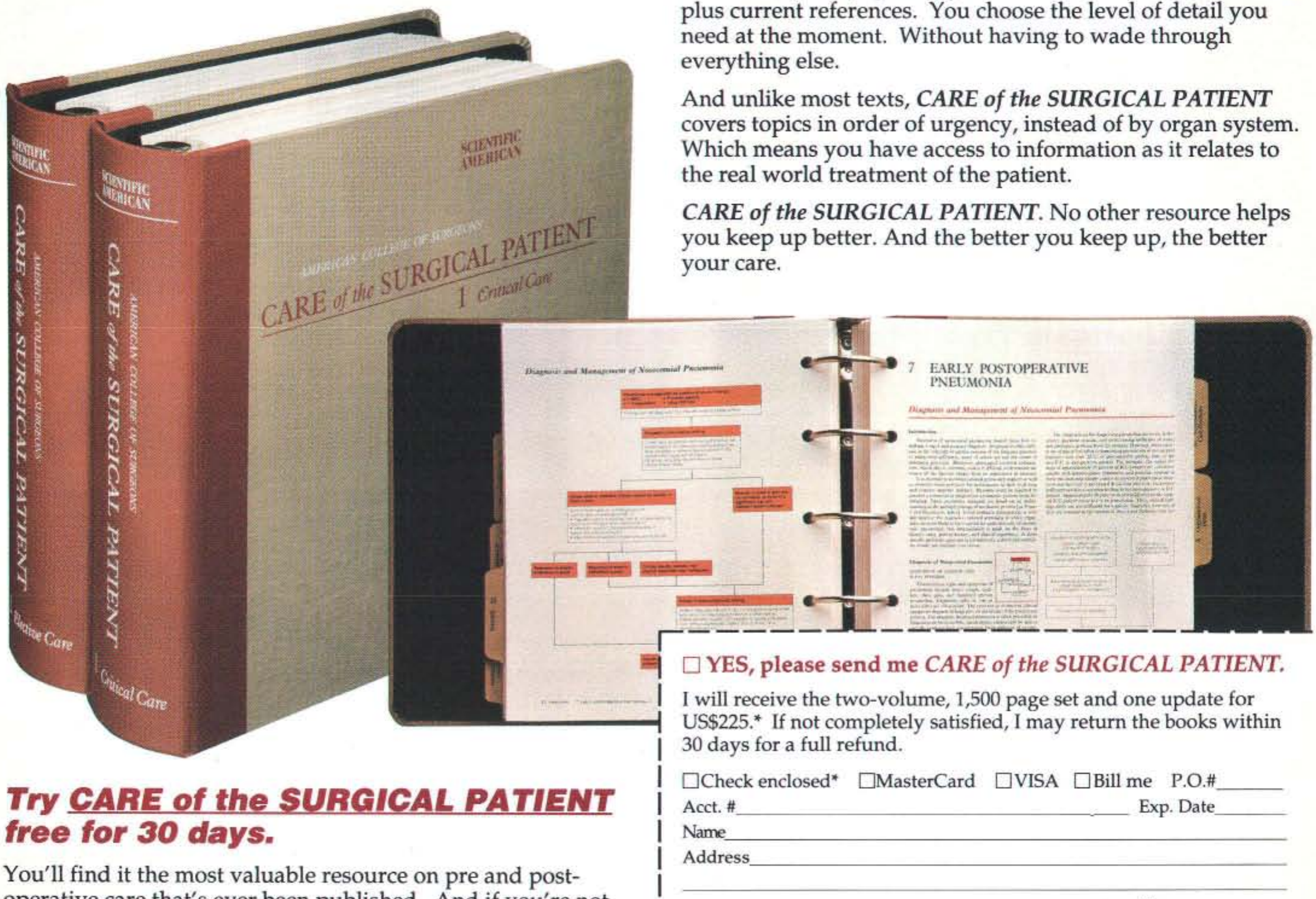
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MATHEMATICAL RECREATIONS

by Ian Stewart

Concentration: A Winning Strategy

With an evil leer on his face, mathemagician Matthew Morrison Maddox turned over the last two cards. "A pair of kings," he sneered. "My infallible good fortune triumphs again!" We were just playing a friendly game. But, for professional reasons, Maddox never misses an opportunity to practice his leer.

Maddox is a master of the art of mathematical trickery. Ordinarily, I would be crazy to bet against him in a game of cards. But that afternoon, I hoped it would pay to be a little loony. I would soon find out. I had been setting up Maddox for weeks, and it was time to collect.

Maddox was beating me at a simple card game, popular the world over. It is generally credited to Christopher Louis Pelman. The game is sometimes called Pelmanism, but it is better known as the Memory Game or Concentration. It is played with a deck containing pairs of matching cards. The deck is shuffled, and the cards are laid out face down. Players take turns flipping over two cards, one after the other. If the cards match, the player removes them and takes another turn; if not, the turn passes to the next player. The game ends when all cards are removed; the player who holds the greatest number of pairs is the winner.

It was a rout. Maddox: 12, Stewart: 0.

"How do you do it?" I asked.

"Do what?" he replied nonchalantly.

"Win every time."

"I suffer from infallible good luck."

"Rubbish."

"Well, Ian, I can tell you that I win at Concentration because I remember all the cards. But it would be unprofessional to reveal my mnemonic tricks."

"Nothing else?" I asked innocently.

"What else is there to a game as simple as this?"

"Good point. Look, Matt, I've got a proposition." I was ready to spring my trap. "It's not really a fair game if all it takes is a good memory, and you've trained your memory to be better than mine. Why don't we even the odds by leaving the cards face up once they've been flipped?"

"As if we both had memories as perfect as mine?"

"Precisely."

He thought about that for a moment. "Okay, if you want. I warn you, I'll still win. I have a natural talent."

"Good. Then you won't mind if I deal the cards." I knew of Maddox's "natural" talent: given half a chance, he'd rig the deck.

"No fair," he cried.

"On the contrary, it's the only fair way. Now, for excitement, what do you say we wager a pound a pair?"

"You mean the loser pays the winner for the difference in the number of pairs they each have got?"

"Right. This way it's just random chance. The scores ought to even out in the long run. Anyway, you claim infallible good luck."

"True." I'd boxed him in; his pride would not let him refuse. My hand strayed nervously to my wallet. I hoped everything would work as planned.

An hour later I had netted £53, and I must admit I enjoyed watching Maddox's leer change into a grimace. It was the first time I'd ever managed to put one over on him. Maddox grabbed the deck from my hand and fanned it out, looking for hidden marks that might be telling me which card was which.

"I swear they're ordinary cards, Matt. No tricks."

He shrugged. "Okay. How do you win nearly every time?"

"I suffer from infallible good luck."

"Haven't we had this conversation before?"

"Could be, Matt."

"Your scam has something to do with those funny moves you keep making, sometimes selecting cards that have already been flipped. Why? You just lose information that way."

"It would be unprofessional to just give my secret away. But I'll tell you what: I'll sell you the trick for a suitable consultancy fee. I know you'd probably like to include it in your act. You could make a fortune." We dickered and then agreed on a fee. I will, however, reveal to all readers of this column, free of charge, what I told Maddox.

There is a winning strategy for Concentration. Moreover, it's easy to remember and far from obvious, the perfect combination for any mathemagical trick. This winning strategy was revealed several months ago by mathematician Uri Zwick and computer scientist Michael S. Paterson of the University of Warwick in England.

Millions of people have played Concentration without resorting to any kind of tactics. At first glance, only memory and chance play a role. But strategy is a factor in Concentration.

Each player generally has the choice of three different types of move. A player can flip two new cards, those that have not previously been turned over. Or she can flip two old cards, those that have been turned. Or she can flip one new card and one old card.

Actually, it's not quite that straightforward, because each player gets to flip two cards, and the result of the first flip may affect what is chosen on the second. The choices boil down to three moves that I call OO, NO and NN. To make an OO move, a player flips two old cards. For the NO move, he first flips one new card, and if that card does not match one already turned over, he flips an old card. If it does match, he removes the first card and its match to get another turn. For the NN move, his first step is again to flip one new card. But this time, if the card does not match one already turned over, he flips a second new card. If the second card matches the first, he removes the matching pair to get another turn.

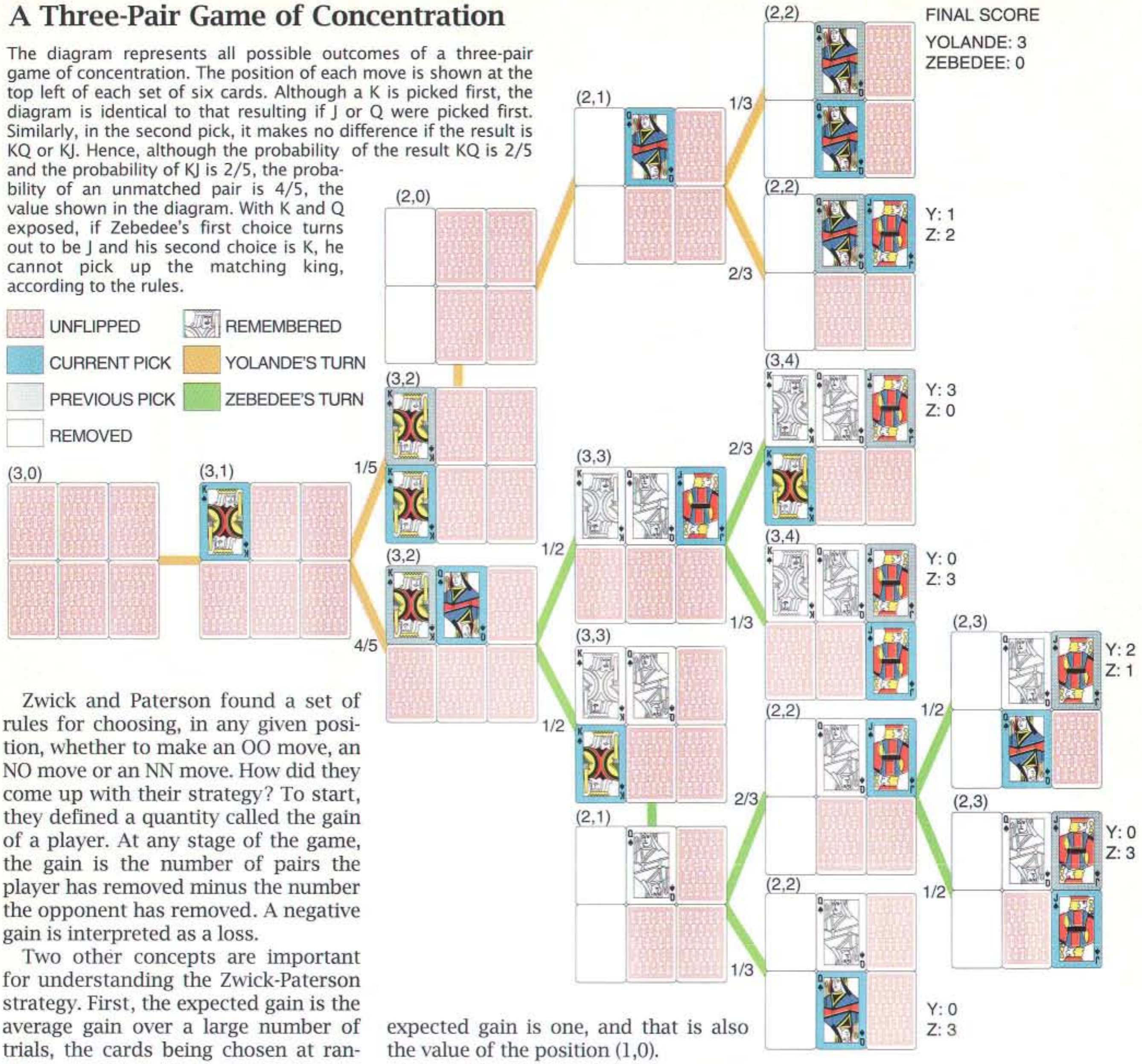
All cards to be flipped are chosen at random, subject to the choice of new or old. The game must start with an NN move. Thereafter all three options exist, unless all flipped cards have been matched and removed.

Incidentally, if in some position it is to one player's advantage to play an OO move, then by the same token it must subsequently be to the other player's advantage to play an OO move. In these cases, the game continues forever and effectively ends in a stalemate.

The strategy devised by Zwick and Paterson depends on how many pairs of cards are left on the table and how many have been flipped (and hence whose faces are known). It does not really matter what the face values of those cards are. The symbols used to specify a position in a game are (n,k), where n is the number of pairs of cards left on the table, and k is the number that have been flipped. For example, if five pairs remain on the table (a total of 10 cards) and four cards have been flipped, then the position is (5,4).

A Three-Pair Game of Concentration

The diagram represents all possible outcomes of a three-pair game of concentration. The position of each move is shown at the top left of each set of six cards. Although a K is picked first, the diagram is identical to that resulting if J or Q were picked first. Similarly, in the second pick, it makes no difference if the result is KQ or KJ. Hence, although the probability of the result KQ is 2/5 and the probability of KJ is 2/5, the probability of an unmatched pair is 4/5, the value shown in the diagram. With K and Q exposed, if Zebedee's first choice turns out to be J and his second choice is K, he cannot pick up the matching king, according to the rules.



Zwick and Paterson found a set of rules for choosing, in any given position, whether to make an OO move, an NO move or an NN move. How did they come up with their strategy? To start, they defined a quantity called the gain of a player. At any stage of the game, the gain is the number of pairs the player has removed minus the number the opponent has removed. A negative gain is interpreted as a loss.

Two other concepts are important for understanding the Zwick-Paterson strategy. First, the expected gain is the average gain over a large number of trials, the cards being chosen at random. Second, the value of a position is the expected gain for the player who makes the first move (assuming that the game begins from that position and is played to the finish). The value of a position that leads to a stalemate, with both players playing OO moves, is by convention 0.

The Zwick-Paterson strategy is optimal in the sense that it maximizes the expected gain. In their strategy, therefore, it can only improve a player's expected gain to remove any available matching pair. Hence, it can be assumed that all such removals are made immediately.

To get a feel for the complexity of the mathematics, think about what happens in a game consisting of a small number of pairs. Suppose Yolande plays Zebedee, with Yolande going first. If they play with just one pair, position (1,0), it is clear that Yolande always wins. Her expected gain is one, and that is also the value of the position (1,0).

What about two pairs, position (2,0)? On her first move, Yolande is forced to flip two cards. If they match, then so do the other two, and she wins, removing both pairs. If not, she leaves two different cards flipped, position (2,2). Any card that Zebedee flips will now match one of these, so he wins, again removing both pairs.

What is the probability that Yolande's first two cards match? Suppose that the cards are a pair of kings and a pair of queens (KK, QQ), and that she first flips a K. Then there are three possibilities for the second card, namely, K, Q or Q. Thus, the probability of a match is 1/3. A similar argument applies if she first flips a Q. The upshot is that with two pairs, Yolande has a 1/3 chance of winning, whereas Zebedee has a 2/3 chance. Yolande's expected gain, and the value of such a position, is therefore $2(1/3) - 2(2/3) = -2/3$. On average, Yolande loses if she starts from position (2,0).

So far there has been no possibility of a choice of moves. But think about (3,0), three pairs, say, KK, QQ, JJ. The possibilities are summarized in the illustration above. Suppose that Yolande's first card is K. The cards remaining unflipped are KQQJJ. Her chance of picking the matching K is 1/5. If she succeeds, the game reduces to a two-pair game, and, as shown before, her expected gain from that position is -2/3. But if Yolande's second card does not match the K (in which case we may assume that the card is a Q), then her turn ends. This event has a probability of 4/5.

Zebedee is now faced with the (3,2) position KQ****, in which the asterisks signify unflipped cards. He has three choices: an NN move, an NO move or an OO move. Suppose he makes an NN move. There are two different possibilities. The first card he flips may match either the K or Q, an event having a probability of 1/2. We may assume the card matches the K. Zebedee can then flip the matching K, remove them and play again from the (2,1) position Q***. From this, he has a 1/3 chance of winning both cards by flipping the remaining Q; otherwise, he loses both pairs. On the other hand, from KQ**** he may flip a J, also with a probability of 1/2, and then his only chance is to flip the other J, which has a probability of 1/3. If he does, then he cleans up; if not, Yolande does.

This scheme is fairly complicated, but fortunately no complicated calculations are needed to see whether an NO move would be better for Zebedee at the stage KQ****. If he uses an NO move instead of an NN move, the analysis is exactly the same, except that he does not have the option of flipping the final card, the one that might just match the J. Instead he leaves Yolande with the (3,3) position KQJ***, and she always cleans up because any new card that she flips will match one that she has already seen. This position is clearly worse for Zebedee. In fact, the expected gains from position (3,2) are 1/3 for an NN move and -2/3 for an NO move. Therefore, if he has any sense, Zebedee makes an NN move.

A similar analysis shows that an NN move is also superior to an OO move. Tracking the probabilities through the diagram, it can be calculated that with three pairs, position (3,0), the first player's expected gain is -1/5—again, a loss. Moral: don't play first when there are three pairs of cards.

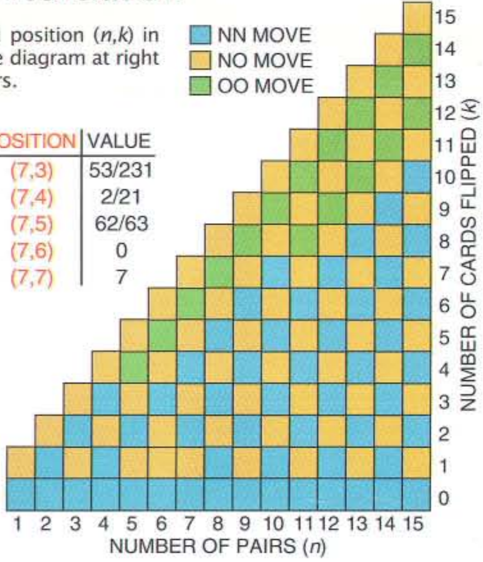
This kind of calculation can be repeated to work out the value of any position. Zwick and Paterson computed the results for up to seven pairs of cards, as given in the table on this page. There are hints of a pattern in the numbers, but nothing striking enough to let us extend the table easily. With this table of values, however, we can work out which type of move is best, starting from any given position. The method is simple in principle but—as I've just shown—messy in practice. Working through the table, we calculate the expected gain for each of the three types of moves and see which is biggest. The results are shown in the diagram next to the table.

The pattern thus revealed leaps to the eye. Each row in the table begins with an NN. When the number of pairs n is even, this NN move is followed by NN, NO, NN, NO and so on. When n is odd, the initial NN move is followed by NO, NN, NO, NN and so on. If, however, the number k of cards flipped is sufficiently large, then the pattern of the sequence changes from NO, NN, NO, NN to NO, OO, NO, OO. This breakpoint occurs almost exactly two thirds of the way along the row.

A Strategy for Perfect Concentration

The table at left shows the value of each position (n,k) in games played with one to seven pairs. The diagram at right indicates the best moves for one to 15 pairs.

POSITION	VALUE	POSITION	VALUE	POSITION	VALUE
(1,0)	1	(5,1)	-1/35	(7,3)	53/231
(1,1)	1	(5,2)	1/7	(7,4)	2/21
(2,0)	-2/3	(5,3)	19/35	(7,5)	62/63
(2,1)	2/3	(5,4)	0	(7,6)	0
(2,2)	2	(5,5)	5	(7,7)	7
(3,0)	-1/5	(6,0)	2/1155		
(3,1)	-1/5	(6,1)	2/1155		
(3,2)	1/3	(6,2)	2/21		
(3,3)	3	(6,3)	13/105		
(4,0)	-4/35	(6,4)	27/35		
(4,1)	4/35	(6,5)	0		
(4,2)	4/15	(6,6)	6		
(4,3)	0	(7,0)	61/1155		
(4,4)	4	(7,1)	61/1155		
(5,0)	-1/35	(7,2)	13/495		



There is one—and only one—exception. The best move from position (6,1) is an NO move, whereas the pattern just described would imply an NN move.

I can now describe the Zwick-Paterson winning strategy for Concentration. From any position (n,k), make the following moves:

- An OO move if $n+k$ is odd and $k \geq 2(n+1)/3$.
- An NO move if $n+k$ is even and $k \geq 1$ or if $k=1$ and $n=6$.
- An NN move in all other cases.

And, of course, remove matching pairs whenever possible.

Surprisingly, although the strategy was discovered only after extensive calculations, it can be applied using simple arithmetic. For example, suppose Yolande is faced with position (100,67). Then $n=100$ and $k=67$. The value of $2(n+1)/3$ is approximately 67.3, so the condition for an OO move fails. An NO move is also unwarranted since $n+k=167$ is odd. Yolande should therefore play an NN move.

The diagram shows that the first interesting case for which an NO move is preferable to an NN move is the position (3,1). I encourage readers to figure out why the NO move is preferable here. To do this, write down the possible patterns of play if an NN move is made and find the expected gain; do the same for an NO move. See which is better. The argument that OO or NO moves "lose information" is irrelevant, because as well as losing information for Yolande, they also deprive Zebedee of the same information, which might be (and here is) to Yolande's advantage.

So now you know how to win at Concentration. First, develop a superpower memory; then play the Zwick-Paterson optimal strategy.

The argument is not yet fully watertight. So far all I've really done is to give some experimental evidence in favor of this strategy. How do I know that the pattern persists for all values of n and k? There might be more exceptions like (6,1), or the pattern might break down altogether for large values of n. Zwick and Paterson prove that the pattern continues forever.

Their proof makes essential use of computer algebra: software that manipulates algebraic expressions in the same manner that a human mathematician would. For example, if told to add $3x^2+2x+5$ and $4x^2+x$, it will reply $7x^2+3x+5$. Unlike more conventional computation, computer algebra can handle symbols as well as numbers.

Maddox leaned back in his chair. "Astonishing! Algebra, probability theory, incredibly complicated calculations demanding computer assistance—and yet the final result reveals a simple pattern that anyone can use to work out the best move in a real game." I could hear the cogwheels in his mind ticking rapidly as he began to ponder how to take advantage of his newly purchased knowledge. Starting by recovering his consultancy fee.

I think I'll keep out of his way for a few weeks.

FURTHER READING

THE MEMORY GAME (EXTENDED ABSTRACT). Uri Zwick and Michael S. Paterson. Mathematics Institute, University of Warwick, March 22, 1991.

BOOK REVIEWS

by Philip Morrison

"Nothing Is Too Wonderful to Be True"

MICHAEL FARADAY AND THE ROYAL INSTITUTION: THE GENIUS OF MAN AND PLACE, by John Meurig Thomas. Adam Hilger, 1991. Distributed in North America by the American Institute of Physics, 335 E. 45th St., New York, NY 10017 (paperbound, $25). **EXPERIMENTAL RESEARCHES IN CHEMISTRY AND PHYSICS**, by Michael Faraday. Bicentennial Edition. Taylor & Francis, 1991 ($55).

On September 22, 1791, Michael, their third son, was born to James and Margaret Faraday. They lived two miles across the Thames from St. Paul's Cathedral. London was then engulfing the countryside, soon to gain its first million people. James, a North Country blacksmith in failing health, had brought his family almost 200 miles from his village smithy down to that hopeful turmoil along the Old Kent Road. But James did not find his fortune there, nor even steady work. The Faradays were often penniless, sometimes hungry; James died before Michael turned 19.

The boy knew the three Rs, but no more, when he left school at the age of 12 to work as errand boy for a kindly local bookseller. Soon he was formally apprenticed to the bookbinder's trade. The gifted, zealous and engaging young bookbinder was apprenticed a second time, in 1813, at the age of 22. This second calling—the result both of good fortune and of a bold and timely act of self-help—was to laboratory research under the most luminous of masters. That man was Humphry Davy, brilliant professor at Count Rumford's Royal Institution in a town house in Mayfair.

A short two years later Michael was given a promotion and a pleasant apartment at the R.I. When he married in 1821, he continued to live at the institution, to work in his laboratory there the rest of his active life and to consult widely. He would publish some 450 papers; not one of those papers cites any formula of the calculus. Faraday had no students or scientific partners in the lab, although for more than 20 years he employed one taciturn assistant. Of all his papers, only two bear the names of co-authors. Effectively alone, he put questions to nature the whole long day.

At 71, loved and celebrated worldwide, he retired with his wife, Sarah, to a country cottage. In his notes for his final lecture we read: "Loss of Memory...cause[s] hesitation and uncertainty...Retire." His energy of mind and his memory continued to fade until his death five years later.

Faraday himself compiled his original papers for publication in book form. By 1855 three volumes presented his most influential work on electromagnetism, the first dynamo, the first transformer, the foundations of electrochemistry, much on dielectrics, some even on plasma. In 1859 a final, more diverse volume appeared, *Experimental Researches in Chemistry and Physics*, reissued for this anniversary with a foreword by John M. Thomas, the distinguished physical chemist who now holds the very Fullerian Professorship at the R.I. that Faraday was given on its first endowment in 1834. (The same publisher who issued this book in 1859 brings it out now in 1991, though no longer from the old printshop in Fleet Street.)

More than 50 papers span Faraday's work outside of electromagnetism in physics, chemistry and technology. They open with his first published paper, of 1816, the chemical analysis of a mineral sample from Tuscany, written at Davy's prompting at a time when "I had no thought of ever writing an original paper on science." One fascinating topic treated in a batch of papers is the infancy of cryogenics, based on an inquiry conceived by Davy and brought to life by Faraday. They saw it as the effort to liquefy and solidify "Bodies generally existing as Gases." The beginning was artfully simple. Prepare a strong bent glass tube a foot or so long. In one end, put a little of the substances that react to form the gas. Seal the tube; heat the reagent end gently, and cool the other end. Temperature is easy to measure from the outside; a clever internal pressure gauge is simply a fine glass capillary sealed at one end. Put a droplet of mercury in the

MICHAEL FARADAY (1791–1867) in an 1830 engraving by J. Cochran capillary, and place the entire little gauge inside the bent tube before it is sealed. The new position the mercury droplet takes as increased pressure compresses the original room air within the capillary yields an easy estimate of tube pressure directly in atmospheres. The scheme works up to 50 or 100 atmospheres. (In the first of the investigations, young Faraday reported, "I have escaped (not quite unhurt) from four explosions." Mask and goggles were soon the fashion.)

Liquid "carbonic acid is a limpid colourless body, extremely fluid," though given to explosions. By 1844 Faraday could add a dozen gases, some as modern-sounding as cyanogen and fluosilicon, to the list of condensed bodies. By then he used two stages of pumps to fill his tubes and a refrigerant bath of dry ice in ether. He could never condense hydrogen, nitrogen or oxygen. It was left to a successor of Faraday's, Sir James Dewar, to liquefy hydrogen, last of the old "permanent gases," right there at the R.I. For the cryogenics of the 20th century that grew around liquid helium (an element never known to Faraday), London would give way to Leiden.

The most unexpected paper here is one given impromptu by Faraday one Friday evening in 1846, according to an unverified legend traditional at the institution. By that account, the shy speaker had bolted away just before lecture time. Faraday had to fill in. (To this day, they guard against another such crisis by locking up every Friday Evening Discourser, placated by a glass of whiskey, half an hour early!) The fine paper is titled "Thoughts on Ray-vibrations." Without using any equations or diagrams, Faraday makes a striking qualitative case for a speculative theory of radiation "as a high species of vibration in the lines of force." The theory "endeavors to dismiss the ether, but not the vibrations," two decades before James Clerk Maxwell's full electromagnetic theory, 50 years ahead of Einstein. Peerless theorist, Maxwell knew, admired, and cited that suggestive talk of fields. Faraday saw atoms less as particles than as the centers of force lines and never picked up the strong clue from his own electrochemical laws: electric charge is atomic.

The Royal Institution is unique: privately and precariously supported, it has sheltered the work of a remarkable constellation of British physicists and chemists ever since its founding in 1799. It is in part a club, in part a research laboratory of small size and great distinction, which boasts to have held more Nobel laureates per square meter than any other lab. It is arguably the birthplace of biomolecular physics as it is of field theory, electrochemistry and plasma physics, and it is "the foremost repertory theatre for the popularization of science in the world."

The founder had hoped that the artisans of London would flock there to attend lectures that might augment their crafts. That never happened, even though Davy was "a coruscatingly brilliant lecturer" who staged breathtaking demonstrations. It was instead the carriage trade, the London quality, who came to admire and to fill the 500 or 600 seats, as they still do.

Mr. Faraday was no less a draw than Davy had been. He initiated two series of lectures that have run ever since, except during wartime. The first, the Friday Evening Discourses—of which he himself delivered more than a hundred—treat some topic of contemporary science or technology for lay audiences, always with demonstrations. They continue to this day, an hour long to the clock tick; 2,000 Friday Discoursers over 165 years form a list too rich to catalogue.

Michael and Sarah Faraday were childless, but they loved children, and early on he undertook a second series of lectures, expressly for children. The Christmas Lectures were a set of half a dozen demonstration talks on a single topic, adapted to a "juvenile auditory." Faraday lectured at 19 Christmases; his last was in 1860, the classic "Chemical History of a Candle." Today the R.I. theater at Christmastime is a lively, audience-filled television studio; those lectures are televised by the BBC to the national audience and in shortened form each summer to the schoolchildren of Japan.

Professor Thomas tells nearly all of this and more, in an illustrated, concise, sunny account of Michael Faraday and the R.I. Faraday's work endures because he was not only an extraordinary experimenter and a creative theorist but a superb writer. "The charm of Faraday's writing is that it gives all the details of his thought and work. He tells of his failures as well as his successes." He makes powerful arguments as limpid as any of his liquid carbon dioxide. Yet John Tyndall, who knew him well, felt behind the sweetness of all Faraday's writing an "excitable and fiery nature" turned by "high self-discipline...into a central glow and motive power of life."

The apprentice bookbinder wrote to a young friend: "I, Sir, I my own self, cut out seven discs (of zinc) the size of halfpennies each. I, Sir, covered them with seven halfpences and . . . pieces of paper soaked in . . . muriate of soda." He had built a voltaic pile. That man, aging and reflective director of the R.I., wrote: "Nothing is too wonderful to be true."

Roaring, Screaming and Purring

The Natural History of the Wild Cats, by Andrew Kitchener. Comstock Publishing Associates/Cornell University Press, 1991 ($27.50).

There is a purity about cats, "the most exclusive of meat-eaters," with no options left save to hunt and scavenge for meat. After 35 million years of predation, cats are ruthless, efficient—and beautiful. We count 37 or so living species, 10 species of big cats who can roar like a lion, the rest smaller ones who can only scream and purr. (They are parted anatomically by the flexibility of the bone at the root of the tongue.)

Dr. Kitchener, an Edinburgh zoologist, has made a readable, up-to-date synthesis of what we know about cats, his account always strengthened by the comparative point of view. There are eight vivid chapters packed with graphs, maps and feline parameters. He includes a cat *Who's Who* in fine color photographs; it shows us most of the small cat species, plus three big cats that, unlike lions and tigers and leopards, are not in the public eye.

First catch your prey? No, first you must detect it. Cats depend on sight and sound. Their sense of smell is not as developed as in other carnivores; the number of their olfactory receptors is only half that of dogs. Cat hearing is acute, with a frequency response that ranges up toward 100 kilohertz, the better to pick up faint, short-range ultrasonic squeaks of rodents. Cats' keen eyes are proverbial. They have a dense retinal streak of cones optimized to pick up horizontal movement where we have a round spot of acute vision. Binocular vision is excellent, though color is less used. Cat vision has a wide dynamic range, good by night and by day. Domestic cats manage well in bright daylight, but they also respond to faint light down to one sixth the flux detectable by human eyes. Interlacing muscle fibers cross over the centerline of the cat's eye, to allow closing of the pupil to a very narrow slit instead of a small round opening like ours. Cat whiskers adjust position depending on the animal's activity; just at the moment of capture they are deployed like a net before the mouth. In the domestic cat, tactile and visual senses map into the

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brain in similar ways, perhaps making complementary images.

The hunt over, the bottom line is digestion. Among carnivores, cats have a short gut for their size. In East Africa, it is observed that vultures sometimes feed on lion feces but never on hyena or wild dog droppings. Analysis concurs; lion, leopard and domestic cat all show a digestive energy efficiency more than 10 percent below the domestic dog. Perhaps we know why. In cats, everything is designed for the climax of the kill, rather similar in all species. Cat design aims toward swift acceleration, no wasted weight for sudden high performance in swift sinuous motion. It is better to digest meat a little wastefully than always to be burdened at that climactic instant by the weight and bulk of a chemical plant not in constant use.

Cats are thought of as solitary, meeting only to fight or mate. In fact, they have a strong system of land tenure, in which males attempt to maintain exclusive hunting and breeding rights in some area. They pursue elaborate patterns of communication, using gestures, sounds and bodily contact—just look and listen. The necessary role of land registry and good fences that functions even when the principals are absent is taken by powerful olfactory signals, deliberately marked on soil and vegetation and dated by natural fading. Cats frugally use their urine and feces in the role of signposts and ink, carefully identifying owner and property by matching symbols.

There are two truly gregarious species: lions and the domestic cat. The field studies are many and subtle. In Her Majesty's Dockyard at Portsmouth, there is a feral population of "domestic" cats that may have been isolated within the dockyard walls for 200 years. They take almost no prey, for the rodents have long been controlled by poison, but they dine well on generous handouts and on garbage. The females there live in prides of a few animals, each on mapped ranges, whereas the males hunt and mate more at large, over an area 10 times that of the female ranges. Something like the polity of the Serengeti lions can be recognized among those naval cats.

One inexpert look at most of the small cat species is enough to suggest the origin of the domestic cat. Any one could be some neighbor's pet. The widely distributed Old World wildcat *Felis sylvestris* is the source of all the genes in today's domestic cats, a domestication some 8,000 years old, on the evidence of an old jawbone found on the wildcat-free island of Cyprus. Four thousand years later striped tabbies were raised and revered in Egyptian temples; ships then spread cats, like rats, worldwide.

The author politely does not mention the earliest phase of cat-human interaction, investigated by C. K. Brain near Pretoria. A million years ago or so our frail hominid ancestors in southern Africa were demonstrably commonplace prey for some big cats of the day, over a time very long by the scale of human history. Somehow the tables were turned. Cunning apefolk were no longer easy game: Was it language, fire or weapons? The cats cannot say.

The Ocean's Hidden Surface

THE DEEP SEA BED: ITS PHYSICS, CHEMISTRY AND BIOLOGY, edited by H. Charnock, J. M. Edmond, I. N. McCave, A. L. Rice and T.R.S. Wilson. The Royal Society, 1990 (£42.60, overseas).

The venerable *Proceedings* and the *Philosophical Transactions of the Royal Society of London* have a lively practice. The Royal Society organizes a few small topical meetings a year. A dozen papers by carefully selected authors, most but not all of them British, address a single problem. They are published as a group in a regular issue of the periodical and separately as well in a slender (if pricey) bound volume. The choice of topics is as wide as the interests of the society; this collection, along with one each on superstrings, on optical technology and on the structure of solids, is current. (The famous thick special volume on the eruption of Krakatan carries the style more than a century into the past.)

Their virtues are easily grasped: very high scientific authority, state-of-the-art coverage, small bulk, brief critical commentary. Their deficiencies are an absence of overall organization, general lack of introductory matter and the dauntingly high technical level that goes with original papers or expert reviews. In short, they are discussions by and for the experts.

This topic at hand is strangely fascinating, not addressed elsewhere at book length. The volume reports a meeting in the spring of 1989 to discuss the bottom of the ocean, the silty, oozy boundary layer, an interest of the 1980s. Mainly, our interest grew from the steady technical advance in oceanographic probes; to some extent, it was impelled by economic proposals to extract minerals or to deliver wastes at the ocean bottom. Endless darkness keeps the region out of sight, hence rather out of mind. But it is a true sur-

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face of the liquid ocean, as large as the sunlit surface we all know, and merits the intense theoretical studies and observations here detailed.

That submarine surface has some physical analogies in any sandy shore, though greatly slowed. The semisolid bottom generates turbulence in the waters by friction as the water flows past, an analogue in time lapse to the swift waves that break on the shore. The real bottom is no abstraction; it is usually not solid rock, not horizontal but sloping, not isothermal but of differing temperatures, not free of eddies or even of a weak ubiquitous tidal rhythm. Slow, large-scale eddies might be 100 miles long and drift past at a tenth of a mile an hour.

The consequences are plain. Four or five miles down there is an extensive layer of mixed sediments and water up to 100 meters thick that slowly changes over days, months and years. Like the beach sands, the bottom material often drifts horizontally. In the water layer just above it, a nourishing fallout from on high wafts past, both tiny particles and large organic masses. The diverse but sparse bottom organisms converge very slowly on any nutritious windfall. What insensate feasts slowly convene down there whenever some decaying whale corpse happens by! Microorganisms, copepods, plump, burrowing marine worms and other deposit feeders—even certain bony fish join the gathering. The book presents one X ray of a core (at no great depth) that shows a cache of food hoarded in its burrow by a lowly yet prudent peanut worm.

Far from the atmosphere, there is less oxygen, and, as we look deeper, there is steadily less life—an order of magnitude decline below surface biomass density for each mile down. Near (above and below) the indefinite bottom, that steady decline of biomass density reverses, to rise fivefold or tenfold. There, too, inorganic chemistry changes, in a cyclical chemistry that is far from straightforward even for manganese and oxygen.

Grand questions are only whispered. The geochemical cycles of carbon and of other elements are not 10-year matters; they are much slower, but we know they are important. At depth lies the great oceanic store of carbon dioxide. We will need to understand all the processes of the centuries, if not of the millennia. That bottom mix is not to be ignored, for the quiet layer in fact is always slowly moving, richer in organic matter than most seawater, and by no means barren of its own avid and shifting web of life.

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ESSAY: QUANTUM ENGLISH

by Anne Eisenberg

Those of you who studied quantum chemistry, quantum electronics or quantum physics may be surprised to hear of a new subject: quantum golf. According to a popular book on the subject, the technique includes a quantum score, a quantum stroke (hit "quantum mechanically, not classically") and even a quantum frame of mind.

It took a while for "quantum" to move from Planck to golf, but the journey had a certain linguistic inevitability.

Scientific terms—those citadels of emotional neutrality, rigor and constancy of meaning—enjoy no special protection in the unequal fight against the odds of popular usage. Despite scientists' best efforts, a technical term is as likely as any other to be mangled as it makes its way into the mainstream.

The terminology of science is coined, *Chambers Technical Dictionary* tells us, to facilitate the precise expression and recording of ideas. But while *Chambers* cautions that "to be safe, one must regard technical language as a language apart from ordinary speech," fewer and fewer people seem to be paying attention. In fact, science and technology are the largest providers of new terms in general currency.

What happens as these terms enter the language? Precision of meaning is usually the first casualty. Consider, for instance, the journey of quantum from its 1900 definition as a small, discrete amount of energy to its popular uses in 1991. First came the switch in scale from microscopic to cosmic, requiring in turn a change from the original "quantum jump" to the late-1960s dictionary entry "quantum leap"—"a sudden, spectacular advance or breakthrough." Initially quantum leap came enclosed within quotation marks, but soon the quotation marks departed, leaving us with, among other uses, a popular television program this past season, *Quantum Leap,* that introduces the weekly struggles of a hero trapped in a time machine.

Quantum is not the only scientific term to be assaulted this way. The "uncertainty principle" was a major victim—Heisenberg watched aghast as it was invoked to explain everything from a decline in religious values to prices on Wall Street.

Technical terms that undergo what linguists call semantic shifts often pass through a stage the dictionary labels figurative. Using this measure, "brain dead" recently moved from a biological description to a metaphor for incompetent, foolish or unreliable. During the past decade, "black hole" has become roughly equivalent to, say, the Bermuda Triangle—a place where car keys and laundry tickets mysteriously vanish. Or it's a place to get stuck, like the Pittsburgh airport.

Sometimes technical terms that move into popular use undergo a restriction in meaning. "Hacker," for instance, was originally an amiable term for a harmless individual up at all hours in front of a computer screen. Then the word was picked up in the press in one context—someone who seeks unauthorized access to a computer data bank—and the term in use by the world at large now means a person who breaks into computers. The positive meaning has been all but obliterated; we even have the "fax hacker"—a person who uses a fax machine to deluge people with unwanted documents. Thus, the criminalization of the hacker.

"Nuclear" has taken a particularly violent trip through popular usage. Its pronunciation became "new-q-lar" when the public followed Eisenhower's lead. (If he can drop bombs, he can use whatever pronunciation he likes, his aides reasoned.) "Nuke" became both noun and verb. In early versions as a noun, it was a shortened form for either nuclear weapon or nuclear-powered electrical generating station. As a verb, it came to mean "to attack with nuclear weapons." Nuke is now a cooking technique—to nuke a slab of pizza is a common task in the kitchen, according to one teenage source. And it is nuked in a "bomb box"—the popular term for a microwave oven, as microwave radiation is confounded with nuclear radiation.

Sometimes the odd use of a technical term is just an author reaching for the right term and grabbing the wrong one. Often a pair of words is interchanged—linguists call these pairs "confusibles"—for instance, concrete (the artificial stone) versus cement (the adhesive) or precise measurements (reproducible in repeated trials) versus accurate ones (close to the actual value).

One way that scientists traditionally guarded against the muddle of daily language was in their austere approach to selecting or coining terms. Greek and Latin stems were the first lines of defense. Michael Faraday, for instance, appealed to the Rev. William Whewell, professor of moral philosophy at the University of Cambridge, for an entirely new set of uncontaminated terms to describe his work. The second defense was a list of negatives: "no metaphor, no humor, no satire, for they may mar the clearness," as Theodore Savory said in *The Language of Science*.

In the past few decades, both defenses have undergone a slight weakening. Today whimsy has made its way into scientific terminology. Perhaps recognizing that no degree of solemnity will protect their words against linguistic pillage, some coiners of terms now use pejorative language, literary allusions, personal references, metaphors and even jokes. Lofti A. Zadeh, father of "fuzzy" logic, boldly decided on fuzzy as the term that best described his theory. Murray Gell-Mann plucked the term "quark" from *Finnegans Wake*. Sheldon Glashow and James D. Bjorken chose "charm," "for we were fascinated and pleased by the symmetry it brought to the subnuclear world." Molecular biologists weld analogies of the alphabet to the genetic code (sentence, word, synonym, palindrome). Computer scientists use literary allusions (Trojan horse), metaphors (computer virus, worm) and humor (vaporware). This relaxed approach may come in part from the recognition that Greek and Latin are no proof against the depredations of popular language. For once introduced to the world at large, technical terms will inevitably shift their meanings.

At the least, the burgeoning number of technical terms indicates, according to *Barnhard's Dictionary,* "an expansion of general interest in technological achievement." Given this compliment, is there any point in laughing—or groaning—at an ad in *The New Yorker* that urges us to buy *Quantum Golf?* Well, as Einstein once said, it's all relative.

ANNE EISENBERG, a professor at Polytechnic University in Brooklyn, is the author of four books on scientific and technical writing, most recently Technical Editing, *to be published by Oxford University Press in early 1992.*

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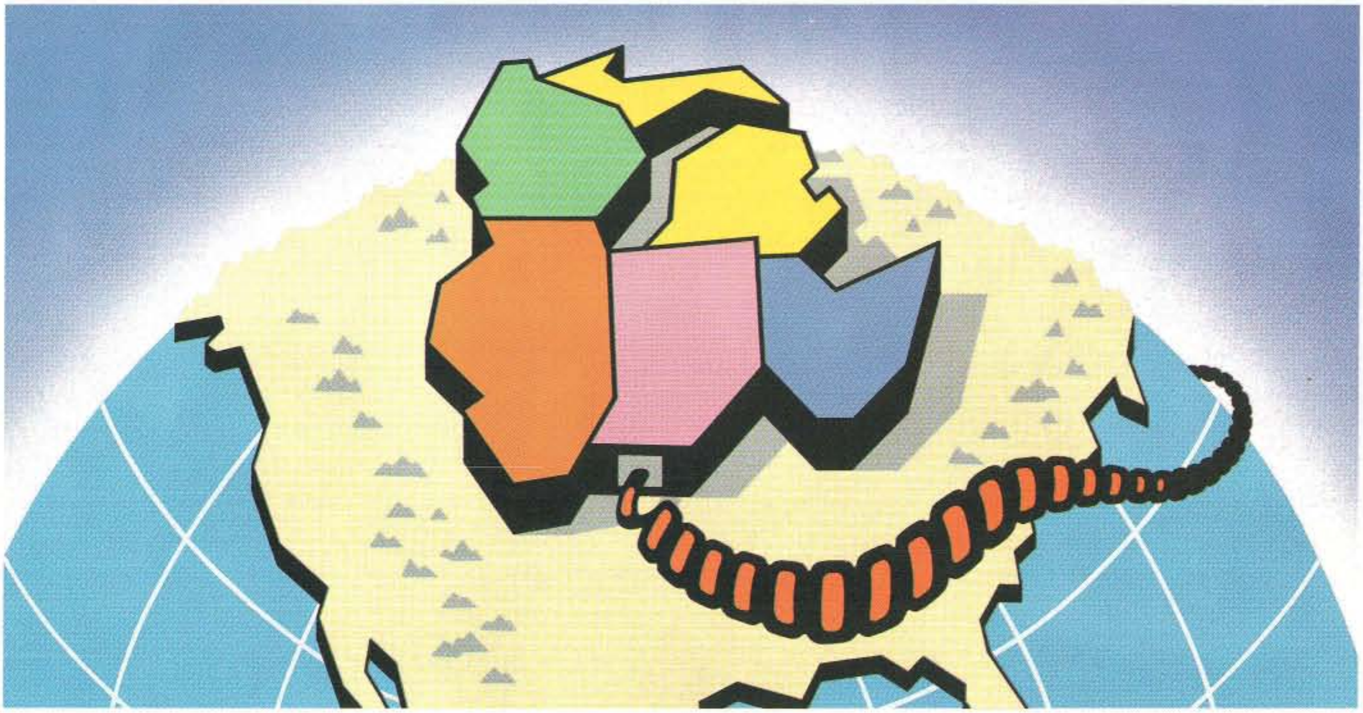

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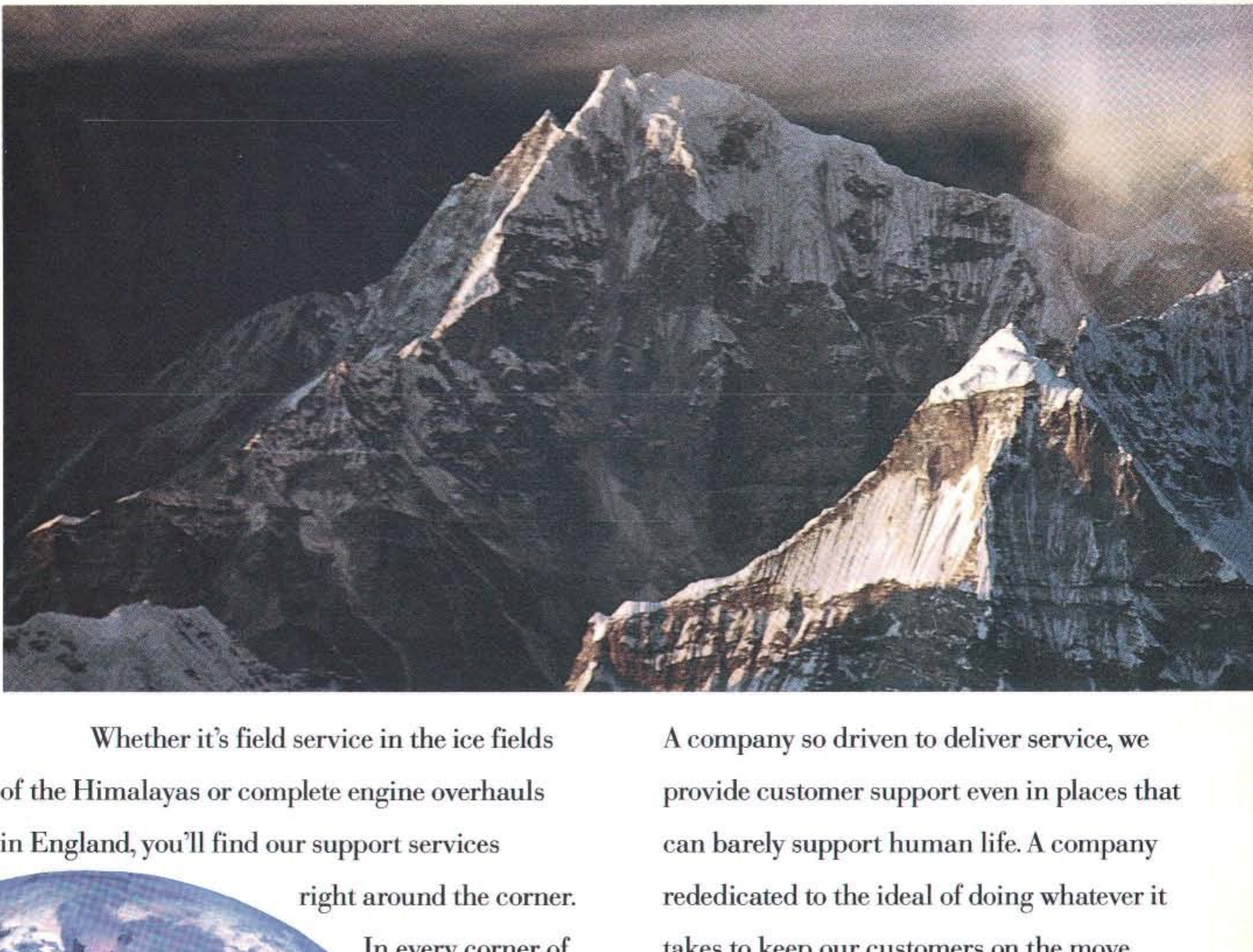

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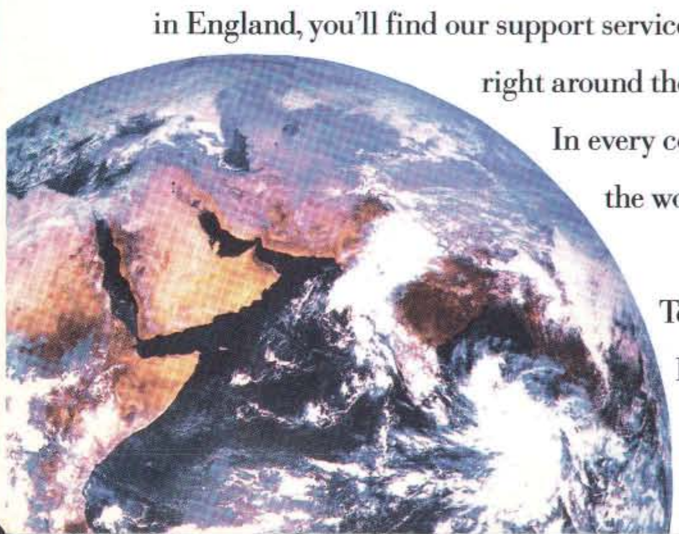

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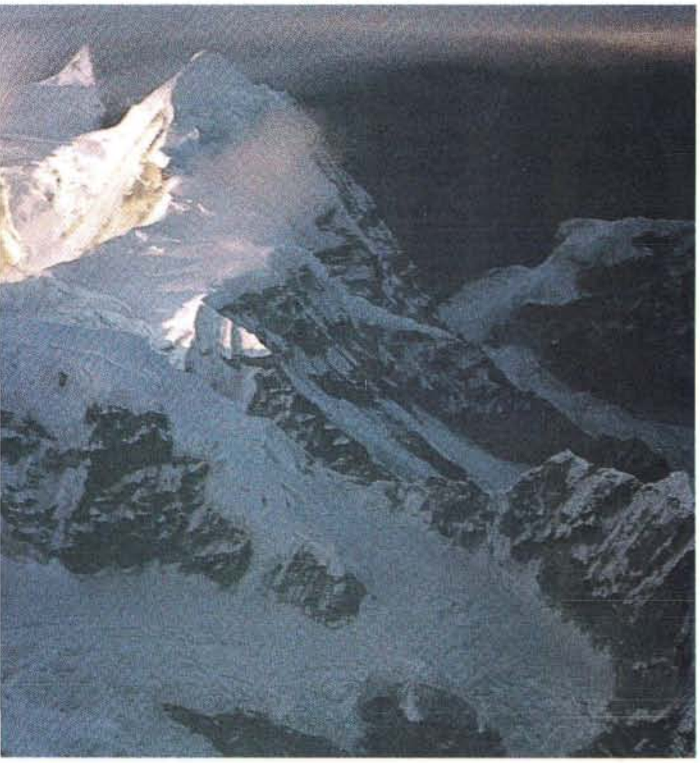

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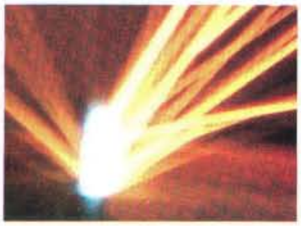

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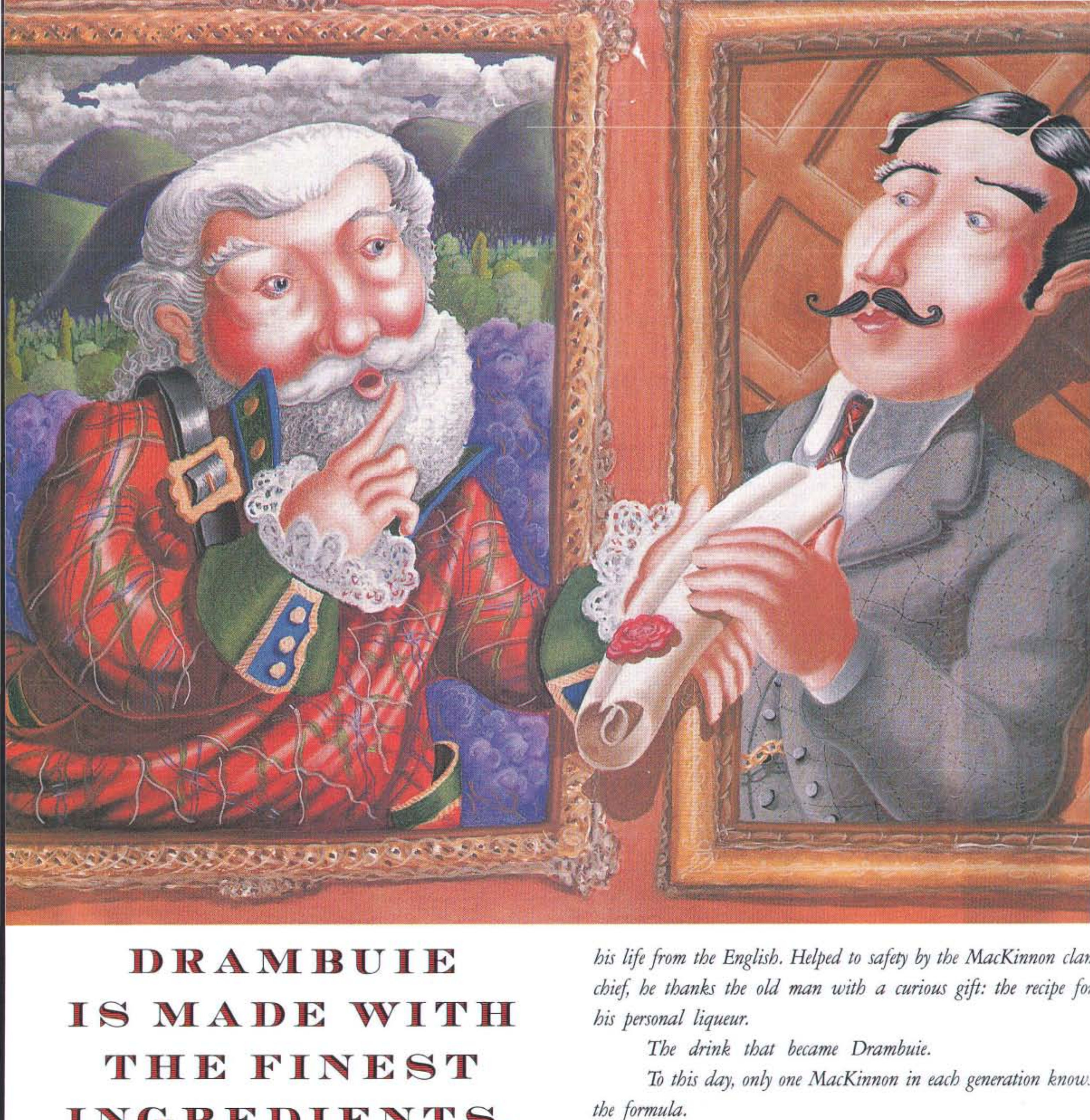

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